Brookhaven National Laboratory

SURGE COLLABORATION

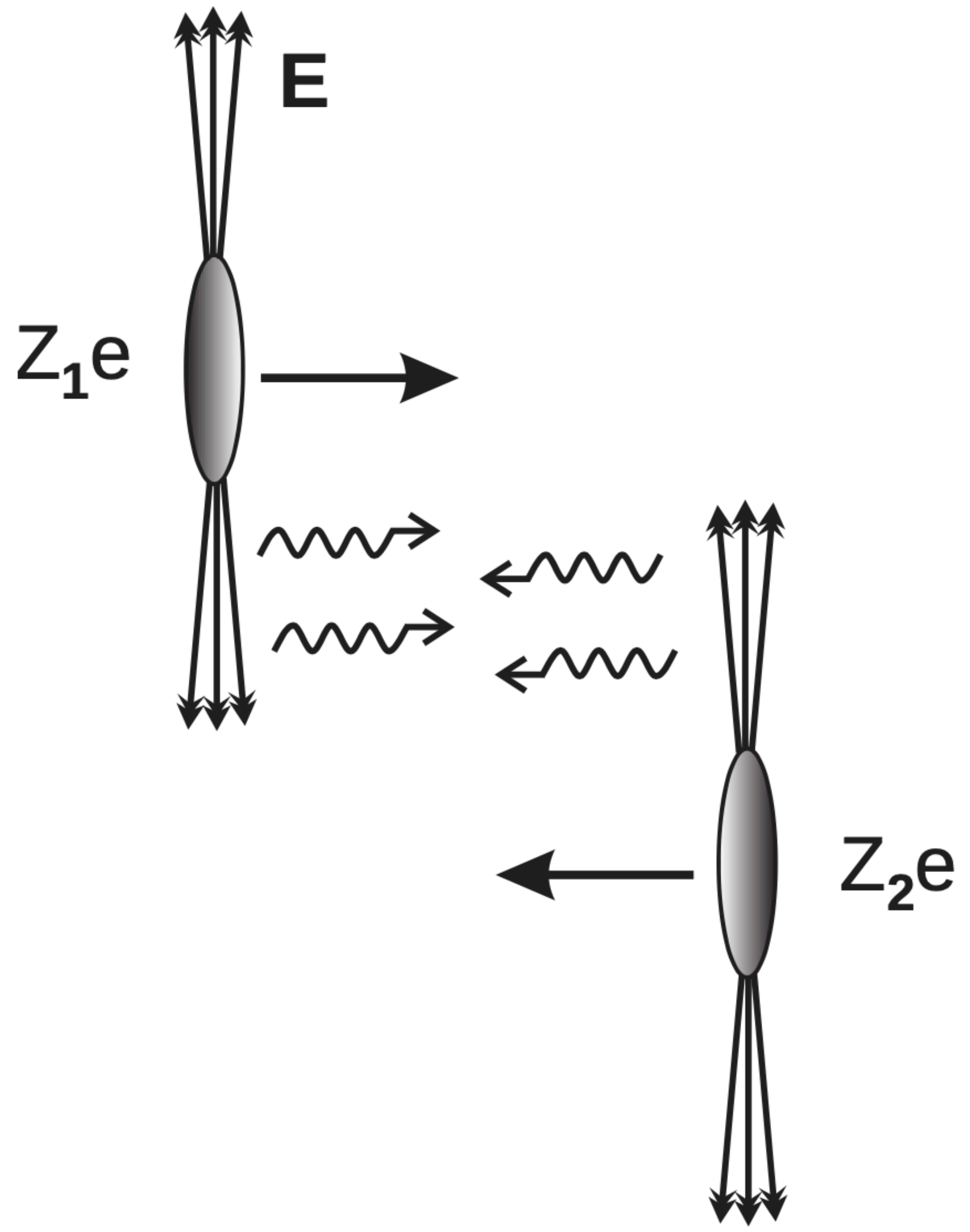
U.S. DEPARTMENT OF ENERGY | Office of Science

NUCLEAR GEOMETRY IN ULTRA-PERIPHERAL COLLISIONS

BJÖRN SCHENKE, BROOKHAVEN NATIONAL LABORATORY

Light Ion Collisions at the LHC
CERN
11/12/2024

Ultraperipheral collisions (UPC)



- At an impact parameter $|b_T| > 2R_A$ nuclei are photon sources
- Photons are quasi-real $Q^2 \lesssim 1/R_A^2$
- High energy $\gamma + \gamma$, $\gamma + p$, $\gamma + A$ at RHIC and LHC
- Consider exclusive vector meson production: Ignoring interference, the cross section is a convolution of photon flux n^{A_1} from nucleus A_1 and the γA_2 cross section (and vice versa):

$$\frac{d\sigma^{AA\to VAA'}}{dt} = n^{A_2}(\omega_2)\,\sigma_{\gamma A_1\to VA_1'}(y) + n^{A_1}(\omega_1)\,\sigma_{\gamma A_2\to VA_2'}(-y)$$

y is the rapidity of the VM and photon energies are $\omega_1 = (M_V/2)e^{y}$, $\omega_2 = (M_V/2)e^{-y}$

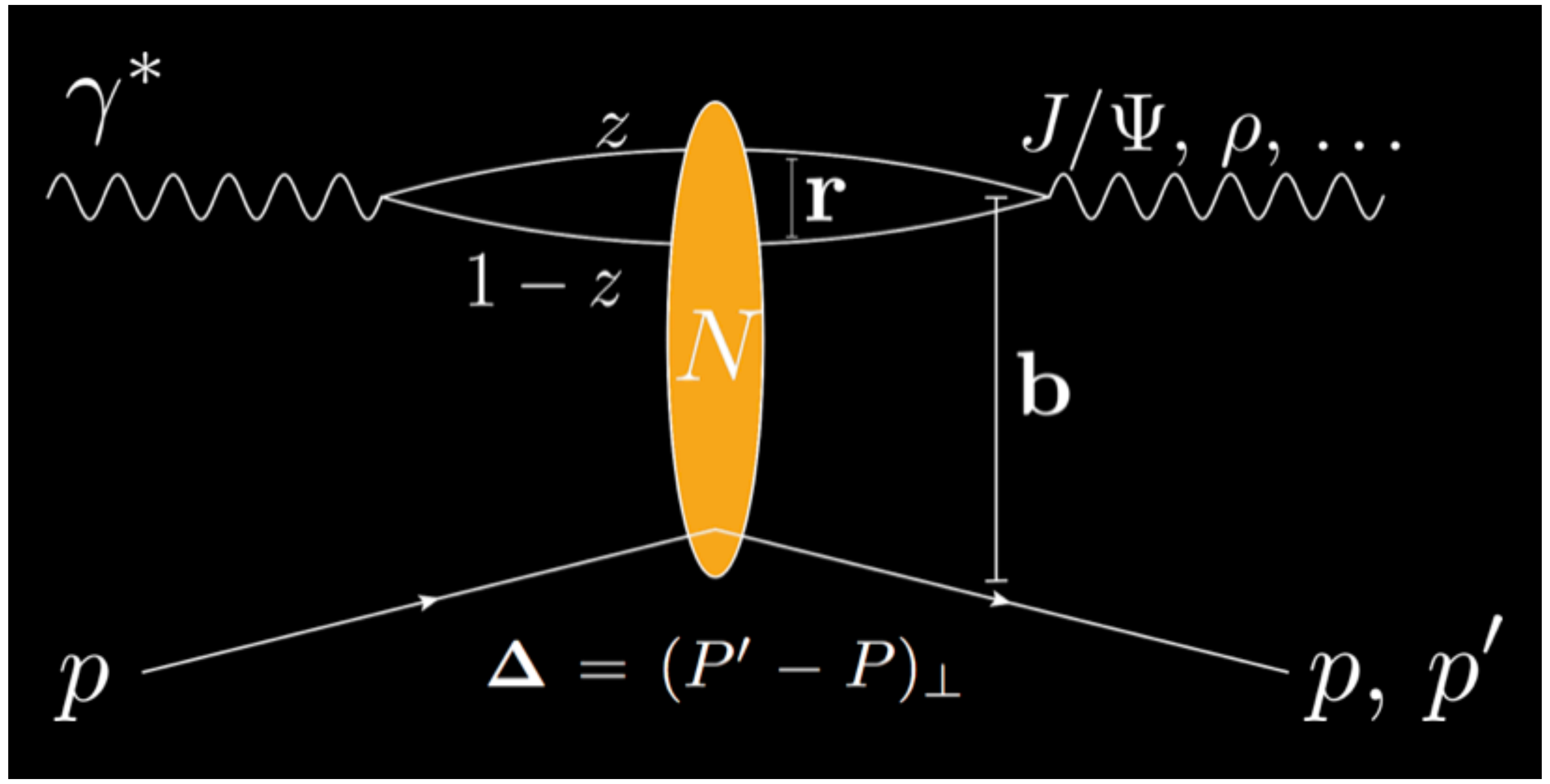
- Interference is important for the differential cross-section in A+A, especially at midrapidity

Vector meson production - Dipole picture

H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301; Phys.Rev. D94 (2016) 034042

High energy factorization:

- $\gamma^* \to q\bar{q} : \psi^\gamma(r, Q^2, z)$
- $q\bar{q}$ dipole scatters with amplitude N
- $q\bar{q} \to V : \psi^V(r, Q^2, z)$



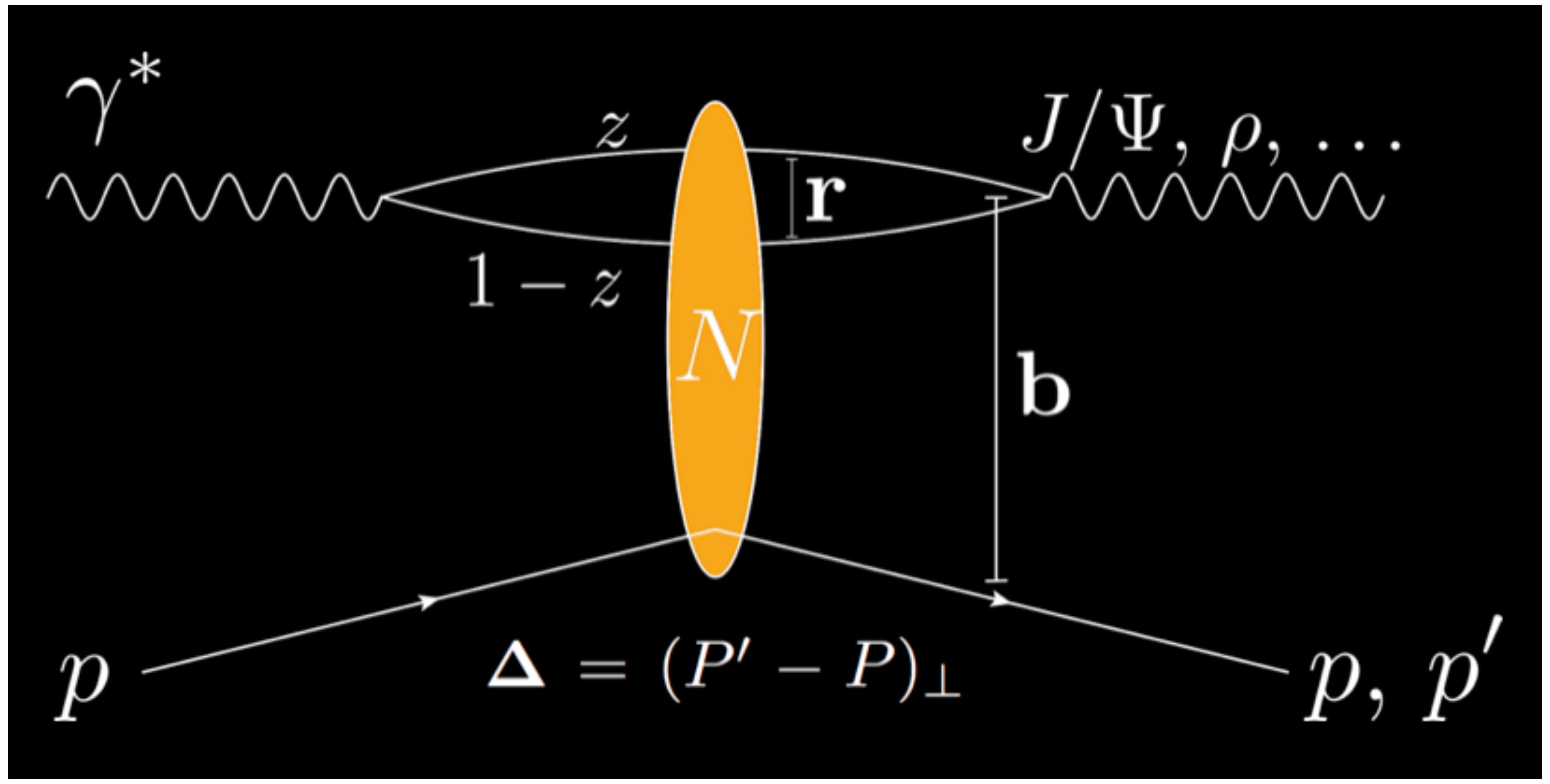
$$A \sim \int d^2b\, dz\, d^2r\, \psi^* \psi^V(\vec{r}, z, Q^2) e^{-i(\vec{b}-(\frac{1}{2}-z)\vec{r})\cdot\vec{\Delta}} N(\vec{r}, x, \vec{b})$$

- Impact parameter ***b*** is the Fourier conjugate of transverse momentum transfer ***Δ***: Access to spatial structure ($t = -\Delta^2$)

Color Glass Condensate Formalism

H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301; Phys.Rev. D94 (2016) 034042

$$N(\vec{r}, x, \vec{b}) = N(\vec{x} - \vec{y}, x, (\vec{x} + \vec{y})/2)$$
$$= 1 - \mathrm{Tr}(\mathrm{V}(\vec{\mathrm{x}})\mathrm{V}^{\dagger}(\vec{\mathrm{y}}))/\mathrm{N_c}$$

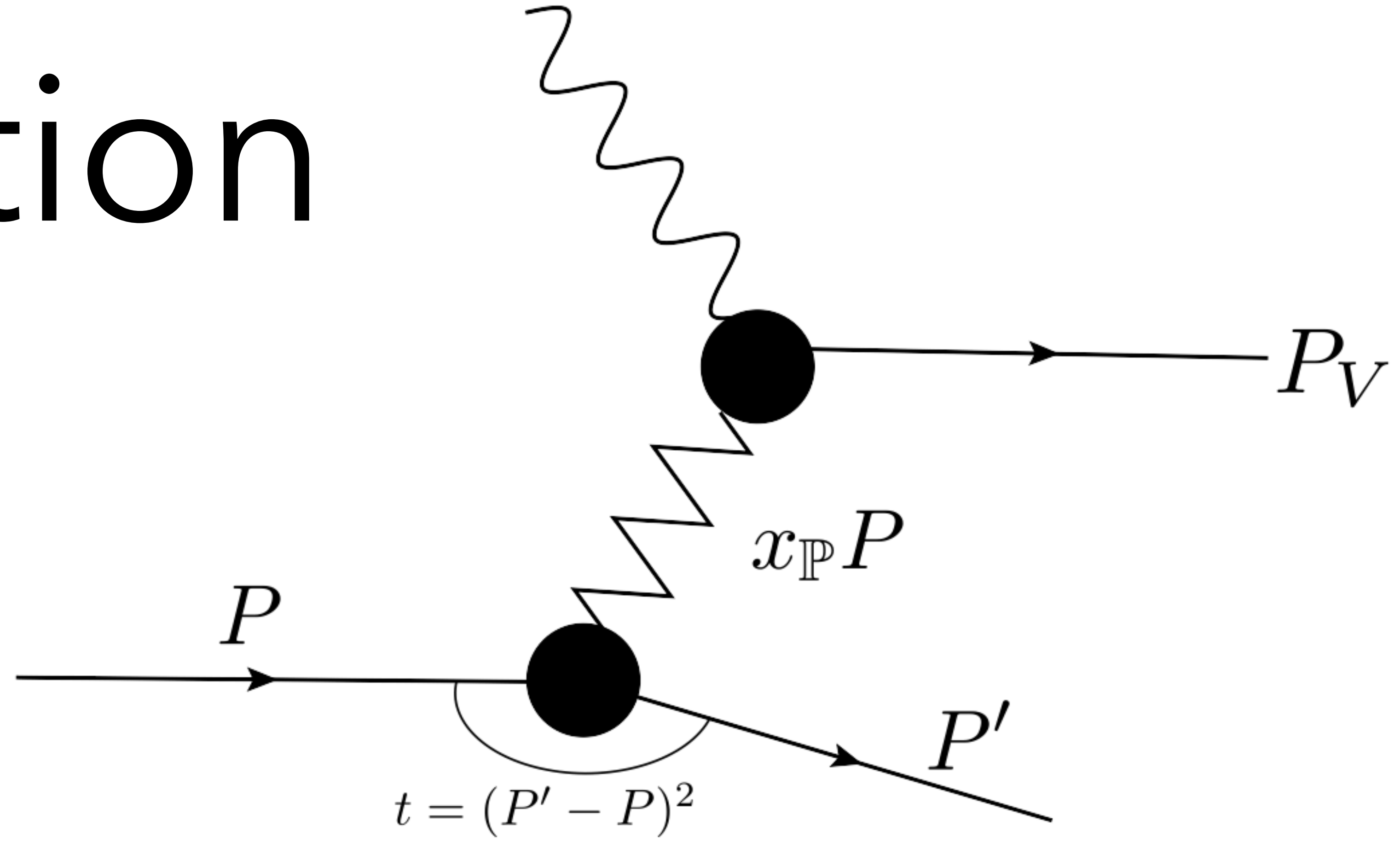


The trace appears at the level of the amplitude, because we project on a color singlet:
Exclusive vector meson production

Compute the Wilson lines using color charges whose correlator depends on $\vec{b}_\perp$ (for example using MV model with impact parameter dependence):

$$\langle \rho^a(\mathbf{b}_\perp)\rho^b(\mathbf{x}_\perp)\rangle = g^2\mu^2(x, \mathbf{b}_\perp)\delta^{ab}\delta^{(2)}(\mathbf{b}_\perp - \mathbf{x}_\perp)$$

Diffractive Vector Meson Production



- Coherent diffraction: $$\frac{d\sigma^{\gamma^* p \to Vp}}{dt} = \frac{1}{16\pi}\left|\left\langle A^{\gamma^* p \to Vp}\left(x_P, Q^2, \vec{\Delta}\right)\right\rangle\right|^2$$

sensitive to the average size of the target

- Incoherent diffraction: $$\frac{d\sigma^{\gamma^* p \to Vp^*}}{dt} = \frac{1}{16\pi}\left(\left\langle\left|A^{\gamma^* p \to Vp}\left(x_P, Q^2, \vec{\Delta}\right)\right|^2\right\rangle - \left|\left\langle A^{\gamma^* p \to Vp}\left(x_P, Q^2, \vec{\Delta}\right)\right\rangle\right|^2\right)$$

sensitive to fluctuations (including geometric ones)

H. Kowalski, L. Motyka, G. Watt, Phys.Rev. D 74 (2006) 074016
A. Caldwell, H. Kowlaski, EDS 09, 190-192, e-Print: 0909.1254 [hep-ph]
M. L. Good and W. D. Walker, Phys. Rev. 120 (1960) 1857
H. I. Miettinen and J. Pumplin, Phys. Rev. D18 (1978) 1696
Y. V. Kovchegov and L. D. McLerran, Phys. Rev. D60 (1999) 054025
A. Kovner and U. A. Wiedemann, Phys. Rev. D64 (2001) 114002

Model impact parameter dependence (in nucleons)

H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301; Phys.Rev. D94 (2016) 034042

1) Assume Gaussian proton shape:

$$T(\vec{b}) = T_{\mathrm{p}}(\vec{b}) = \frac{1}{2\pi B_{\mathrm{p}}} e^{-b^2/(2B_{\mathrm{p}})}$$

2) Assume a substructure of the nucleon. For example Gaussian distributed and Gaussian shaped hot spots:

$$P(b_i) = \frac{1}{2\pi B_{\mathrm{qc}}} e^{-b_i^2/(2B_{\mathrm{qc}})}$$ (angles uniformly distributed)

$$T_{\mathrm{p}}(\vec{b}) = \frac{1}{N_{\mathrm{q}}} \sum_{i=1}^{N_{\mathrm{q}}} T_{\mathrm{q}}(\vec{b} - \vec{b}_i)$$ with N_{q} hot spots; $$T_{\mathrm{q}}(\vec{b}) = \frac{1}{2\pi B_{\mathrm{q}}} e^{-b^2/(2B_{\mathrm{q}})}$$

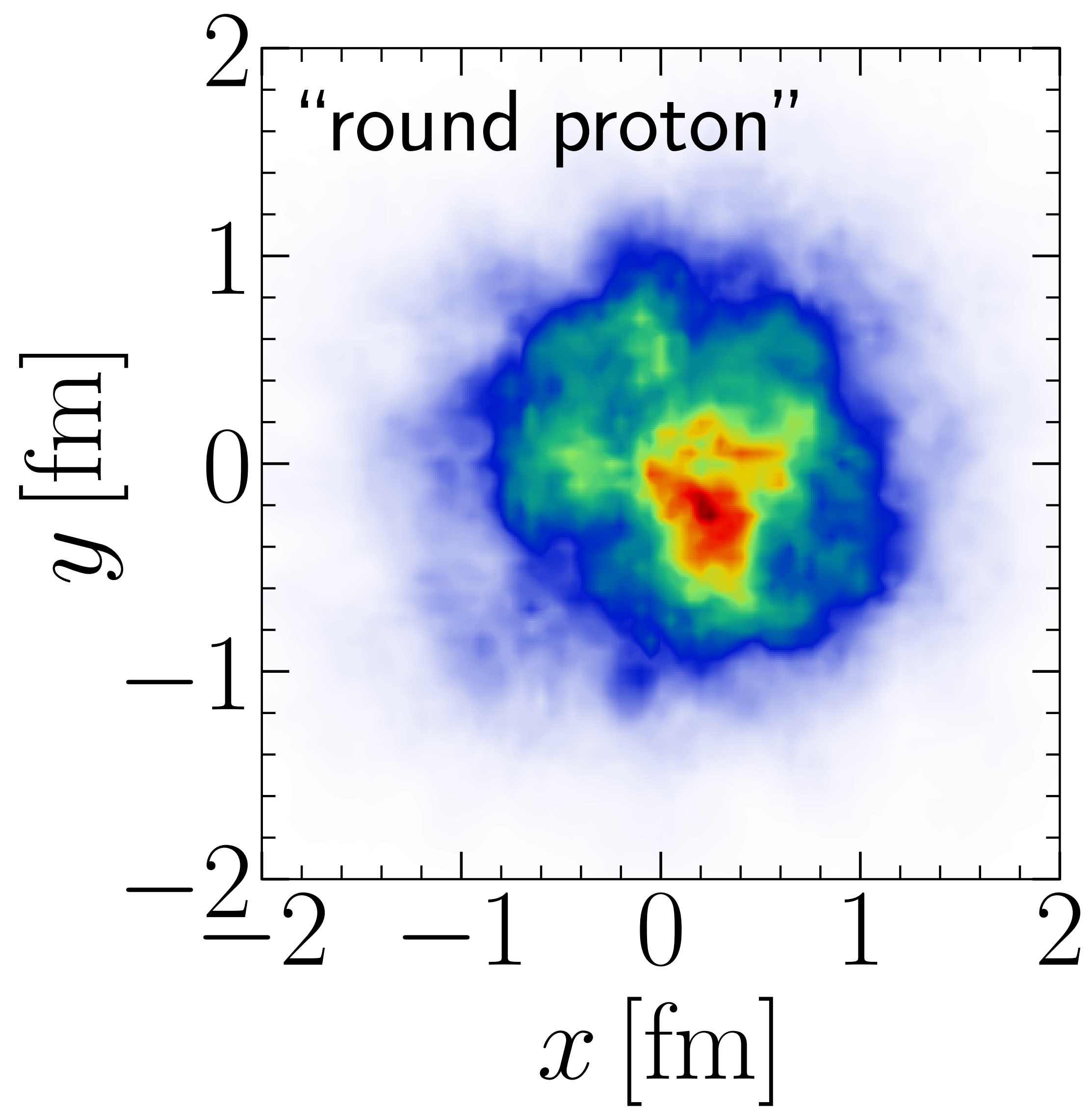
Diffractive J/ψ production in e+p at HERA

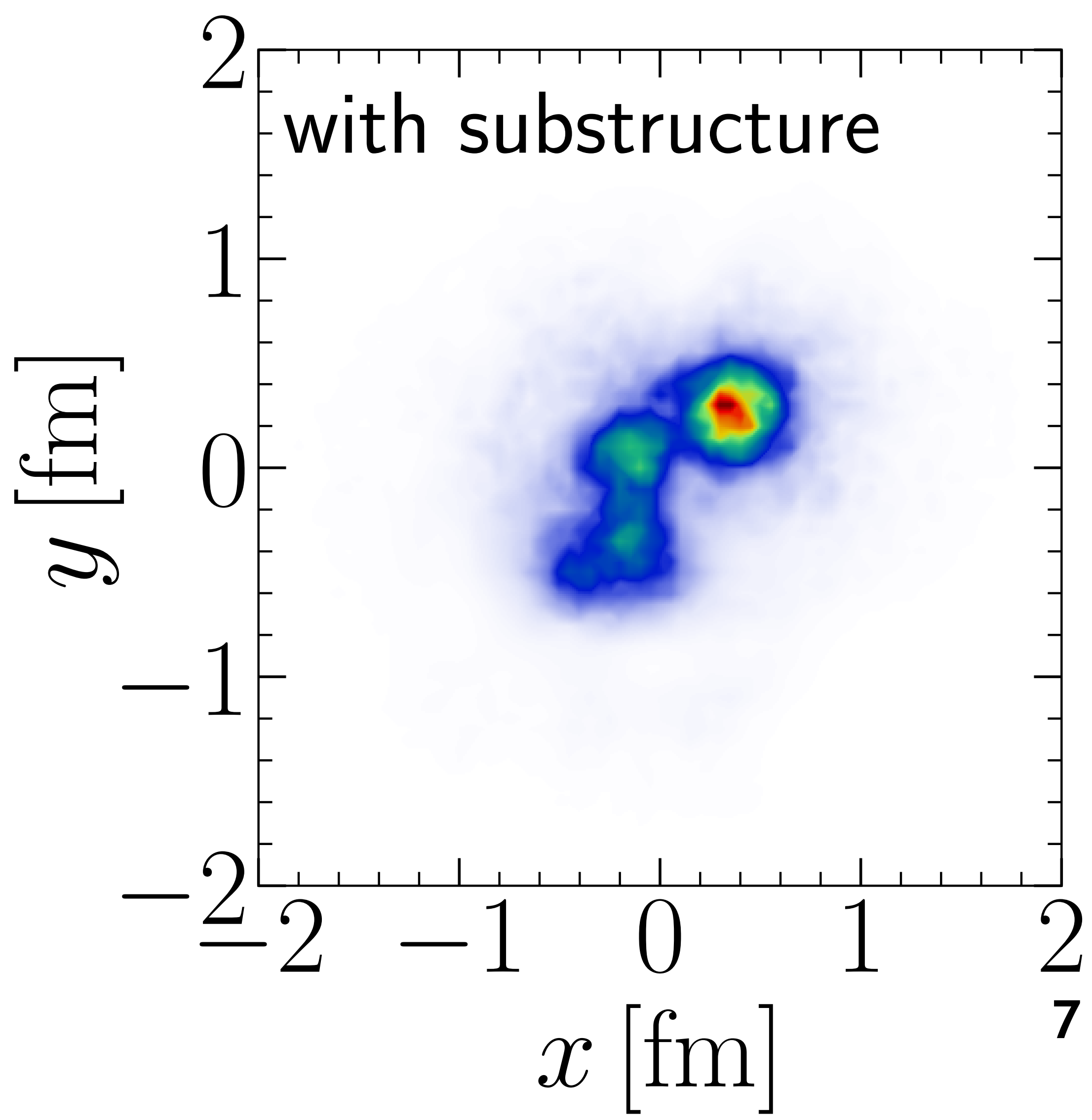
Nucleon parameters B_{q}, B_{qc}, can be constrained by e+p scattering data from HERA

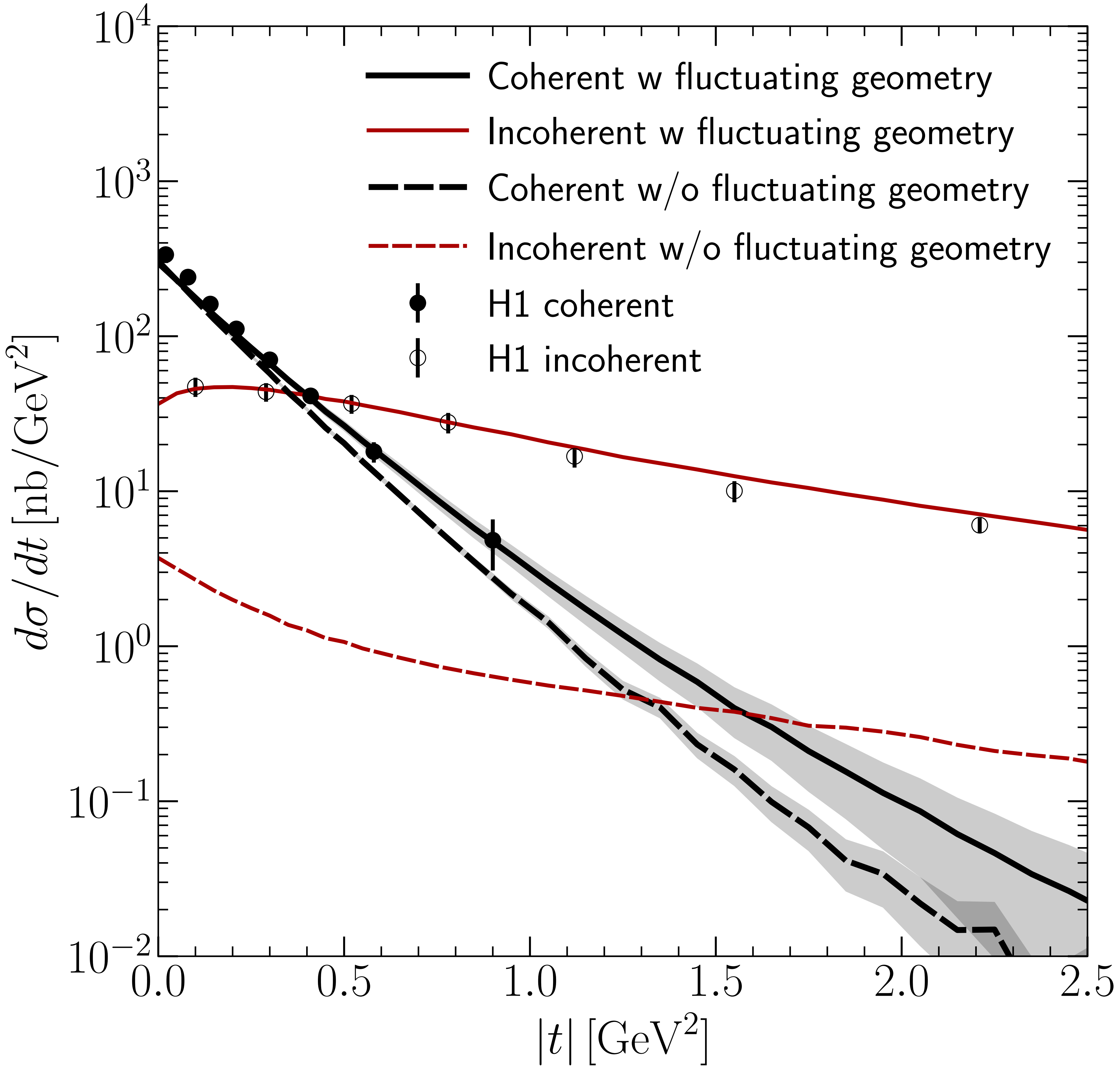
Exclusive diffractive J/Ψ production in e+p:

Incoherent x-sec sensitive to fluctuations

H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301
Phys.Rev. D94 (2016) 034042
also see:
S. Schlichting, B. Schenke, Phys.Lett. B739 (2014) 313-319
H. Mäntysaari, Rep. Prog. Phys. 83 082201 (2020)
B. Schenke, Rep. Prog. Phys. 84 082301 (2021)







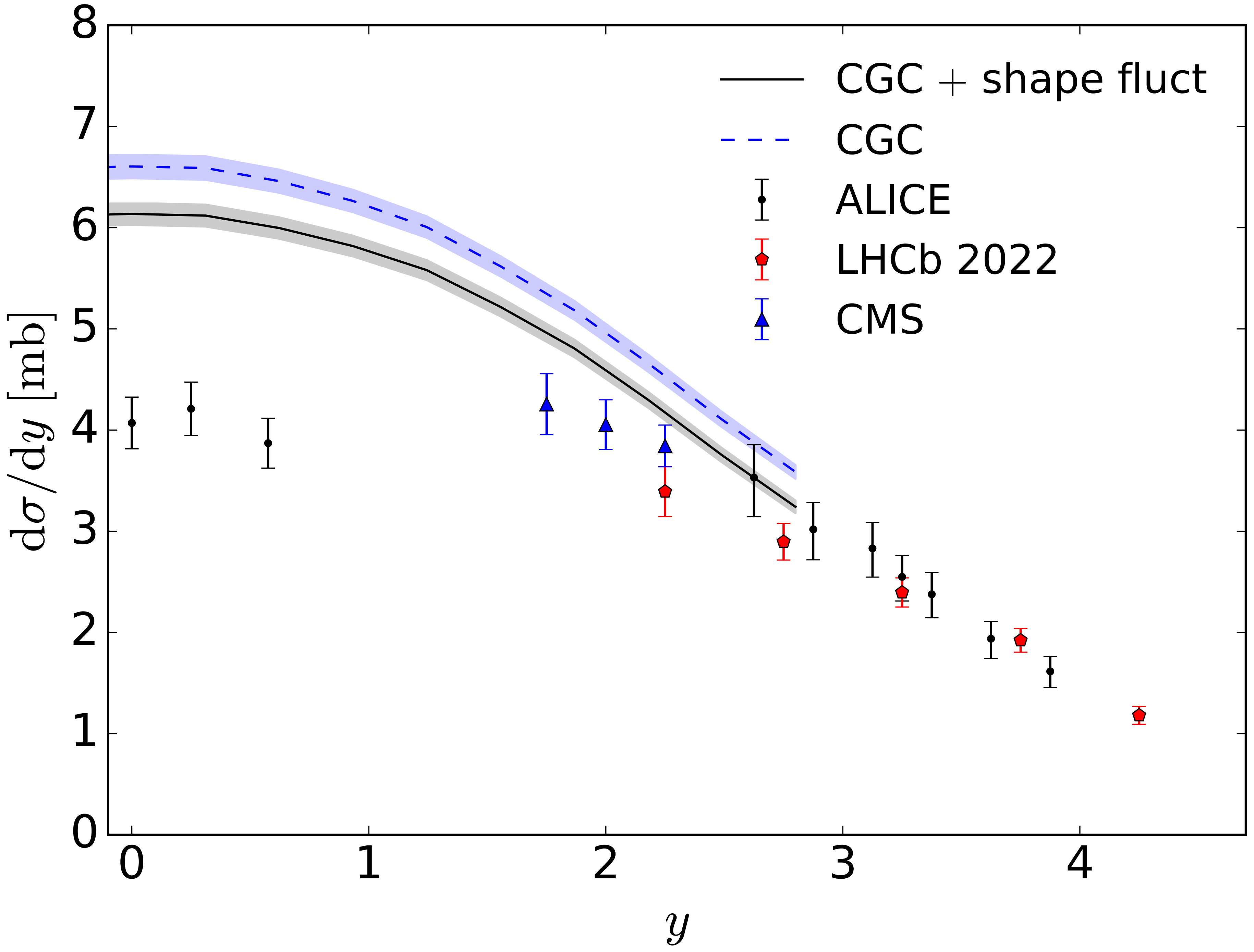
H1 Collaboration, Eur. Phys. J. C73 (2013) no. 6 2466

Back to UPCs: Coherent cross section

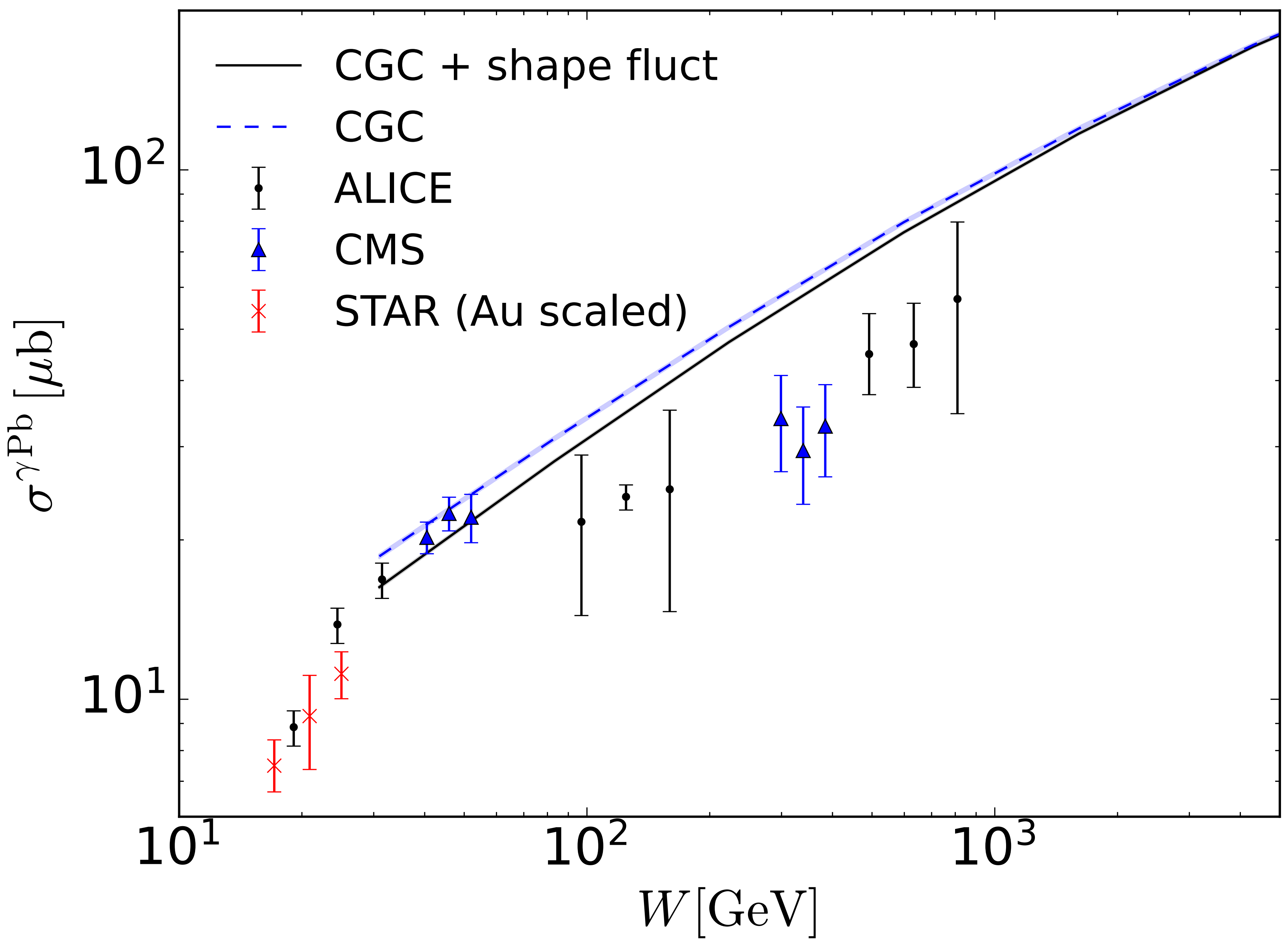
H. Mäntysaari, F. Salazar, B. Schenke, Phys.Rev.D 106 (2022) 7, 074019 and arXiv:2312.04194

Calculation is constrained by HERA J/ψ production data

Pb+Pb → Pb+Pb+J/ψ



γ+Pb →J/ψ +Pb



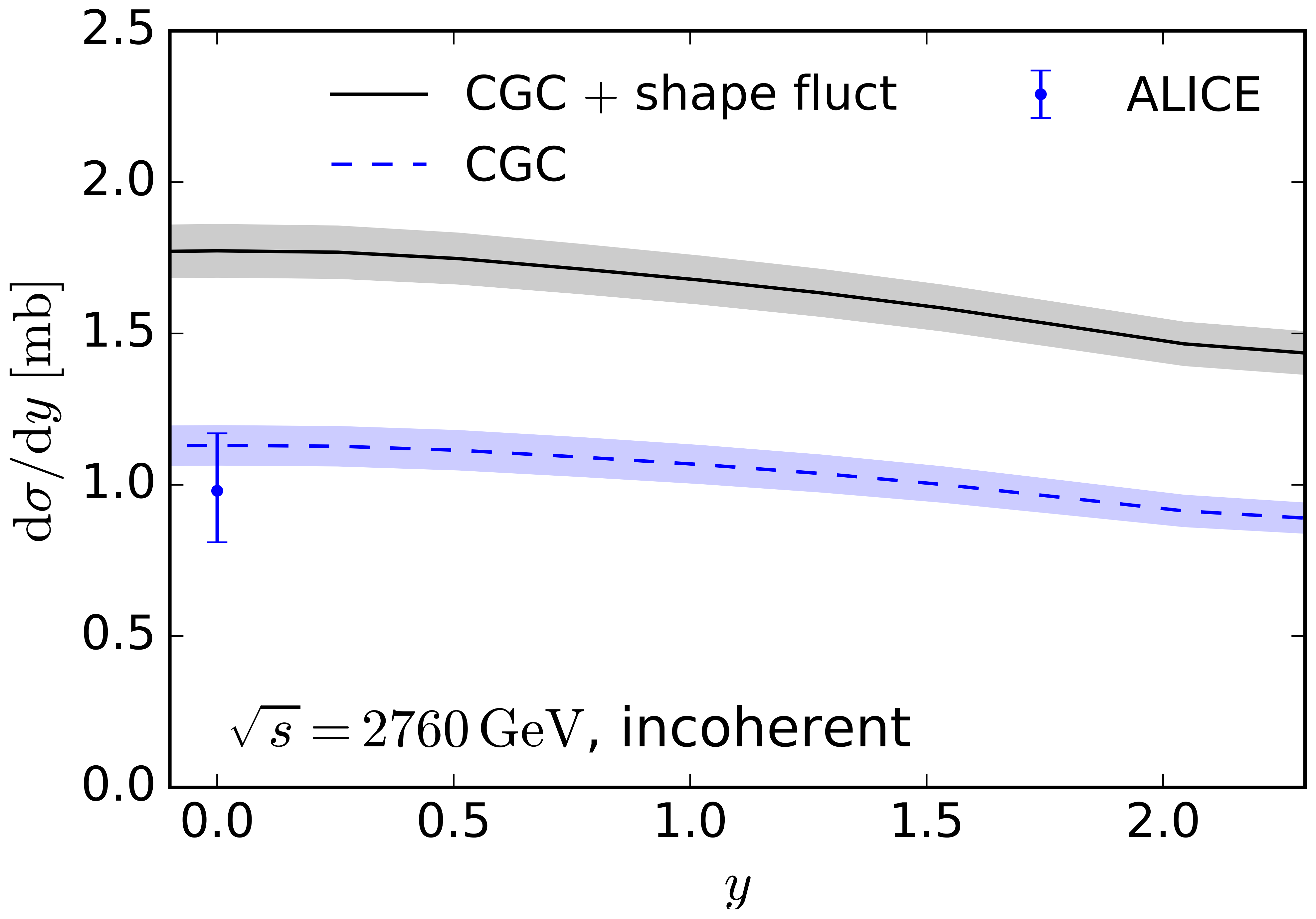
Larger suppression when including shape fluctuations: Hotter hot spots; larger local Q_s

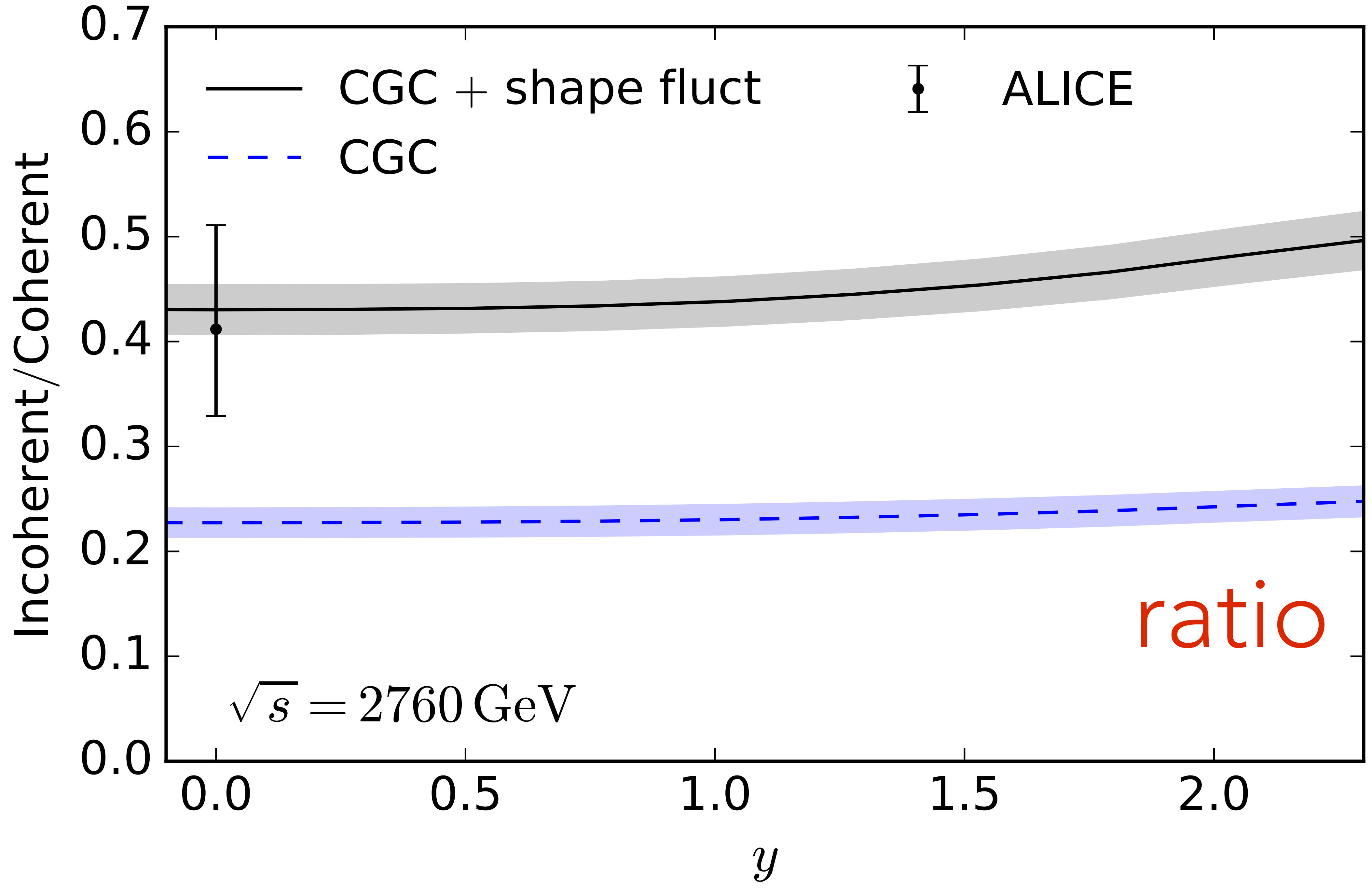
ALICE Collaboration, S. Acharya et. al., Eur. Phys. J. C81 (2021) no. 8 712 [arXiv:2101.04577]
CMS Collaboration, A. Tumasyan et. al., arXiv:2303.16984
LHCb Collaboration, R. Aaij et. al., JHEP 06 146 (2023) [arXiv:2206.08221]

Incoherent cross section

H. Mäntysaari, F. Salazar, B. Schenke, Phys.Rev.D 106 (2022) 7, 074019

Pb+Pb → Pb+Pb*+J/ψ





More fluctuations when including shape fluctuations → larger incoherent cross section

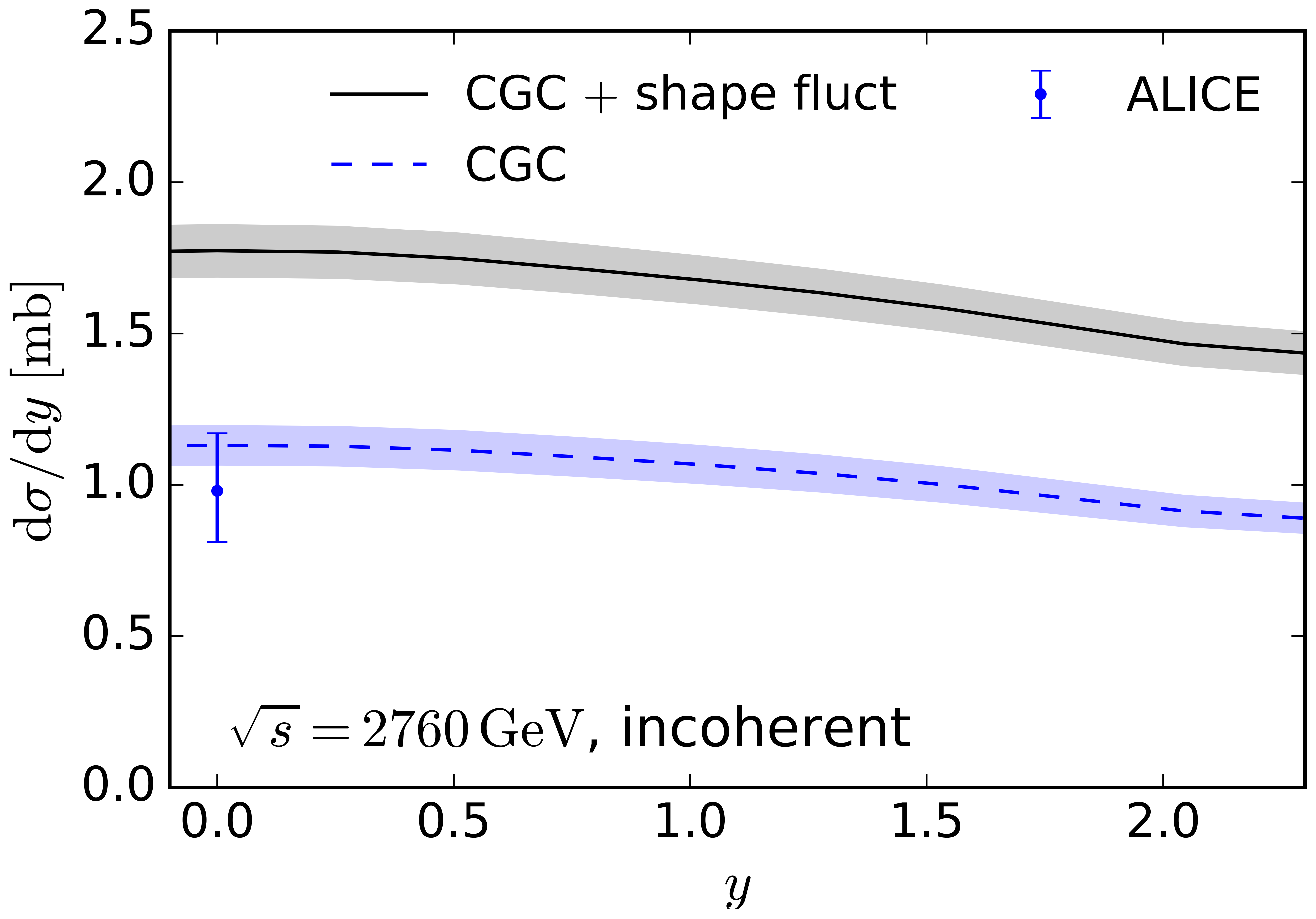
Ratio of coherent to incoherent well described (both coh. and incoh. overestimated)

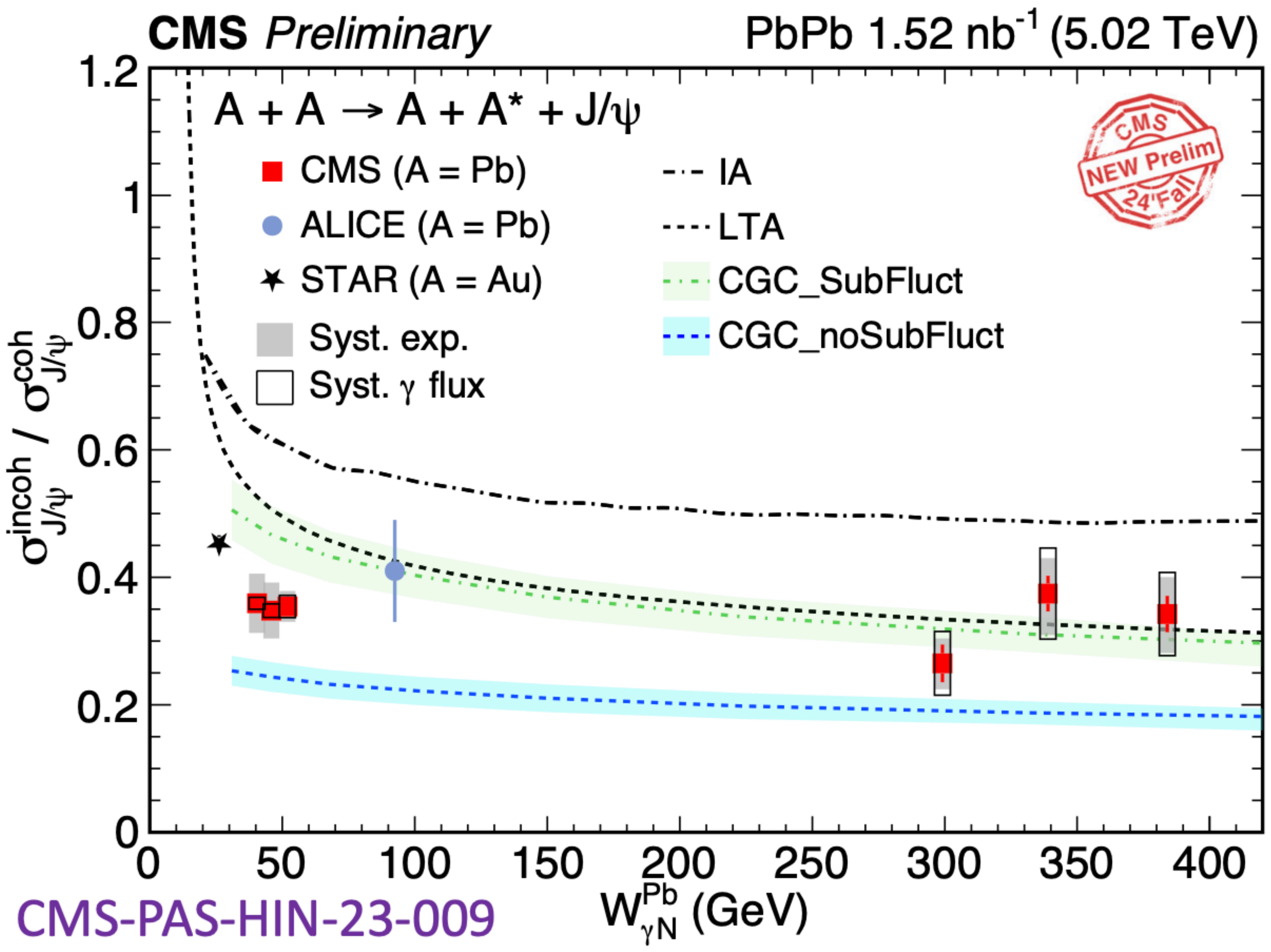
ALICE Eur. Phys. J. C73 (2013) no. 11 2617

Incoherent cross section

H. Mäntysaari, F. Salazar, B. Schenke, Phys.Rev.D 106 (2022) 7, 074019

Pb+Pb → Pb+Pb*+J/ψ





CMS-PAS-HIN-23-009

new CMS results shown at Hard Probes 2024
CMS-PAS-HIN-23-009

More fluctuations when including shape fluctuations → larger incoherent cross section

Ratio of coherent to incoherent well described (both coh. and incoh. overestimated)

ALICE Eur. Phys. J. C73 (2013) no. 11 2617

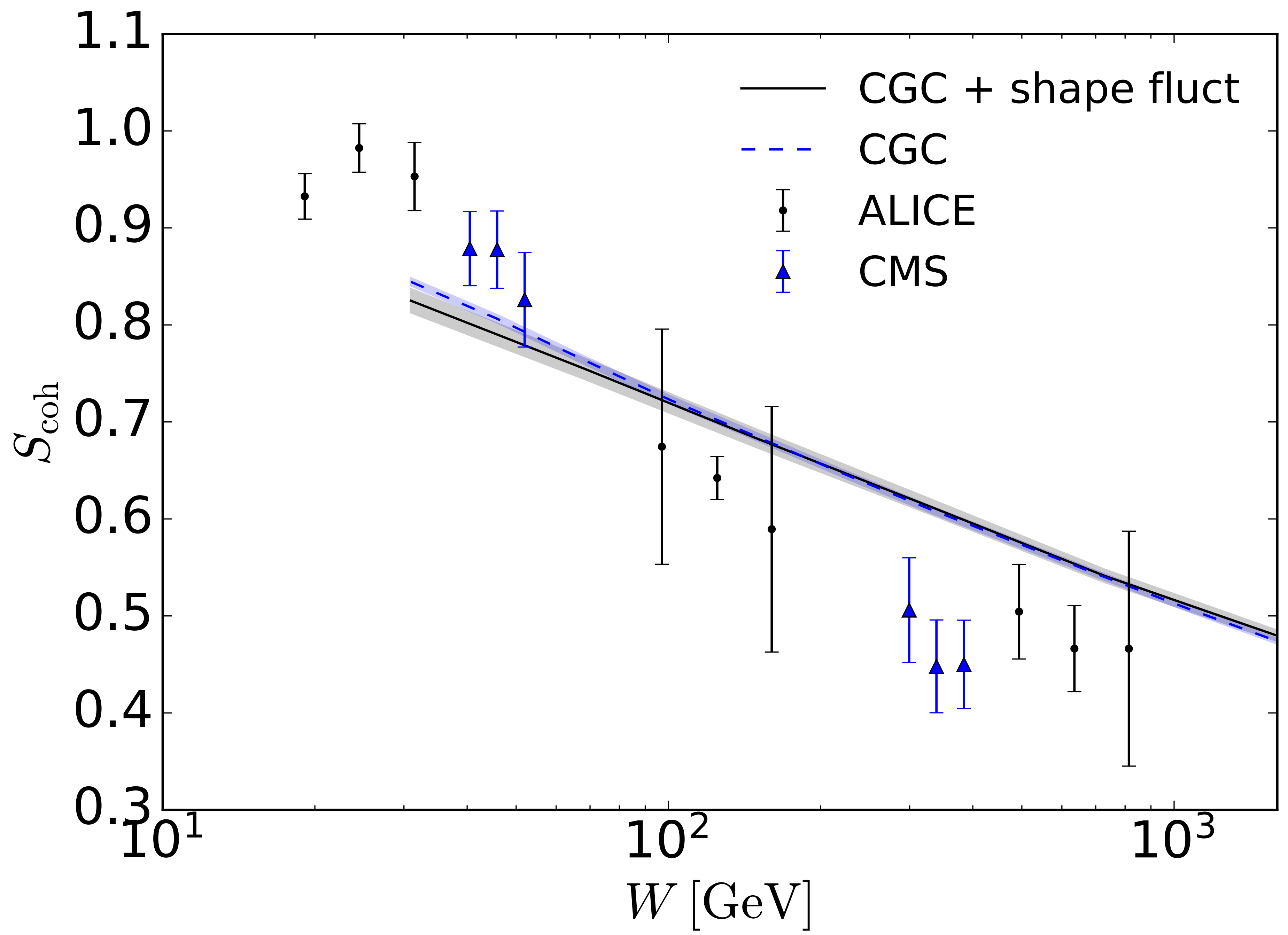
Nuclear suppression

H. Mäntysaari, F. Salazar, B. Schenke, Phys. Rev. D 109, L071504 (2024)

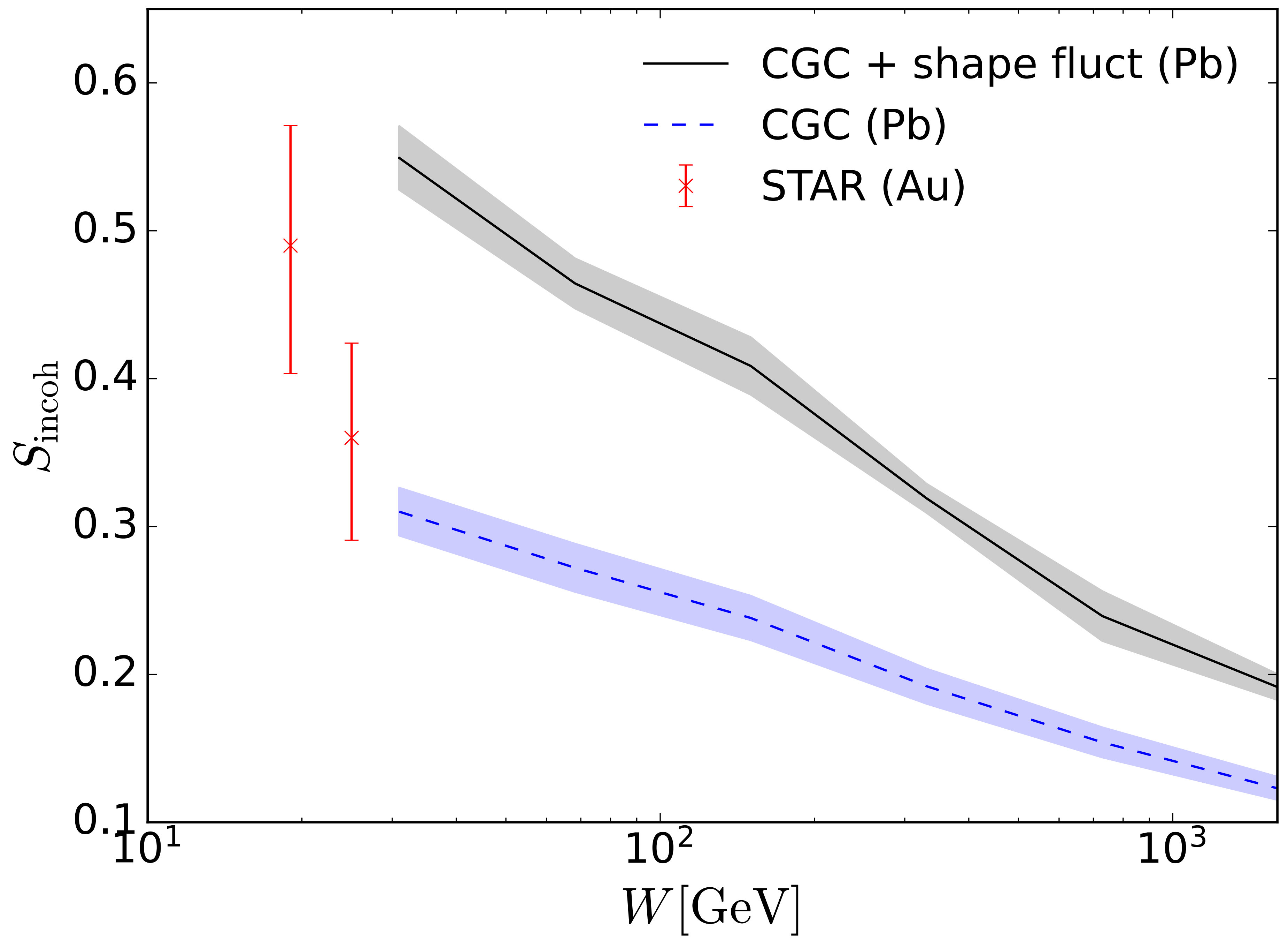
$$S_{\mathrm{coh}} = \sqrt{\frac{\sigma^{\gamma A}}{\sigma^{\mathrm{IA}}}} \qquad \sigma^{\mathrm{IA}} = \frac{\mathrm{d}\sigma^{\gamma p}}{\mathrm{d}t}(t=0)\int_{-t_{\min}} \mathrm{d}t\,|F(t)|^2$$

$$S_{\mathrm{incoh}} = \frac{\sigma^{\gamma+A\to \mathrm{J}/\psi+A^*}}{A(\sigma^{\gamma+p\to \mathrm{J}/\psi+p^*}+\sigma^{\gamma+p\to \mathrm{J}/\psi+p})}$$

Coherent



Incoherent



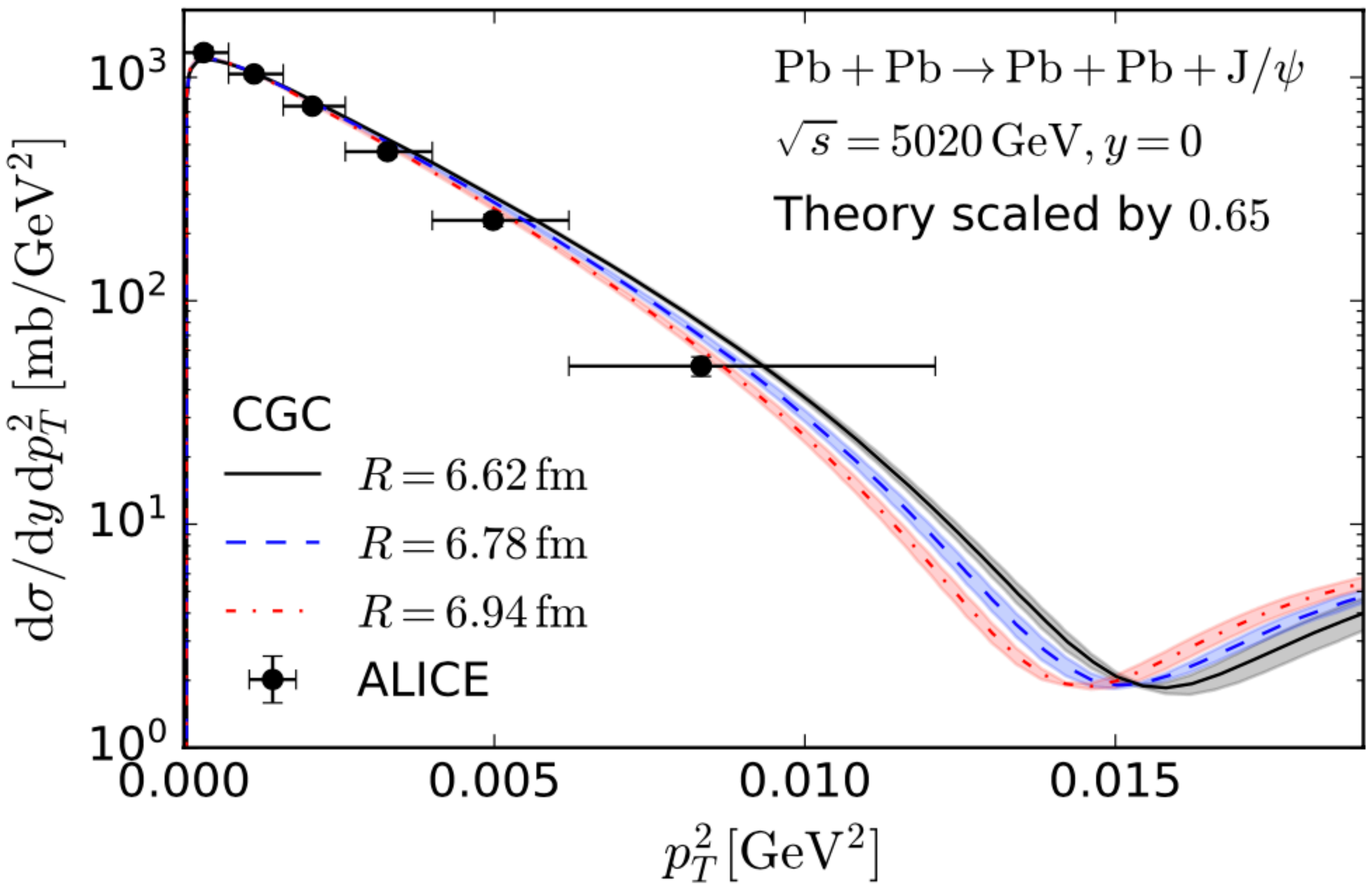
CMS Collaboration, A. Tumasyan et. al., Phys.Rev.Lett. 131 (2023) 26, 262301

ALICE Collaboration, S. Acharya et al, JHEP 10 119 (2023) [arXiv:2305:19060]

STAR Collaboration, Phys.Rev.Lett. 133 (2024) 5, 052301

Effect of the nuclear size

H. Mäntysaari, F. Salazar, B. Schenke, Phys.Rev.D 106 (2022) 7, 074019



ALICE Collaboration, Phys.Lett.B 817 (2021) 136280

- Steep enough spectrum obtained with a larger nucleus
- Neutron skin effect?

STAR measurements of diffractive photo production of ρ mesons and study of interference patterns in the angular distribution of $\rho^0 \to \pi^+\pi^-$ decays also indicate that strong-interaction nuclear radii of Au and U are larger than the charge radii

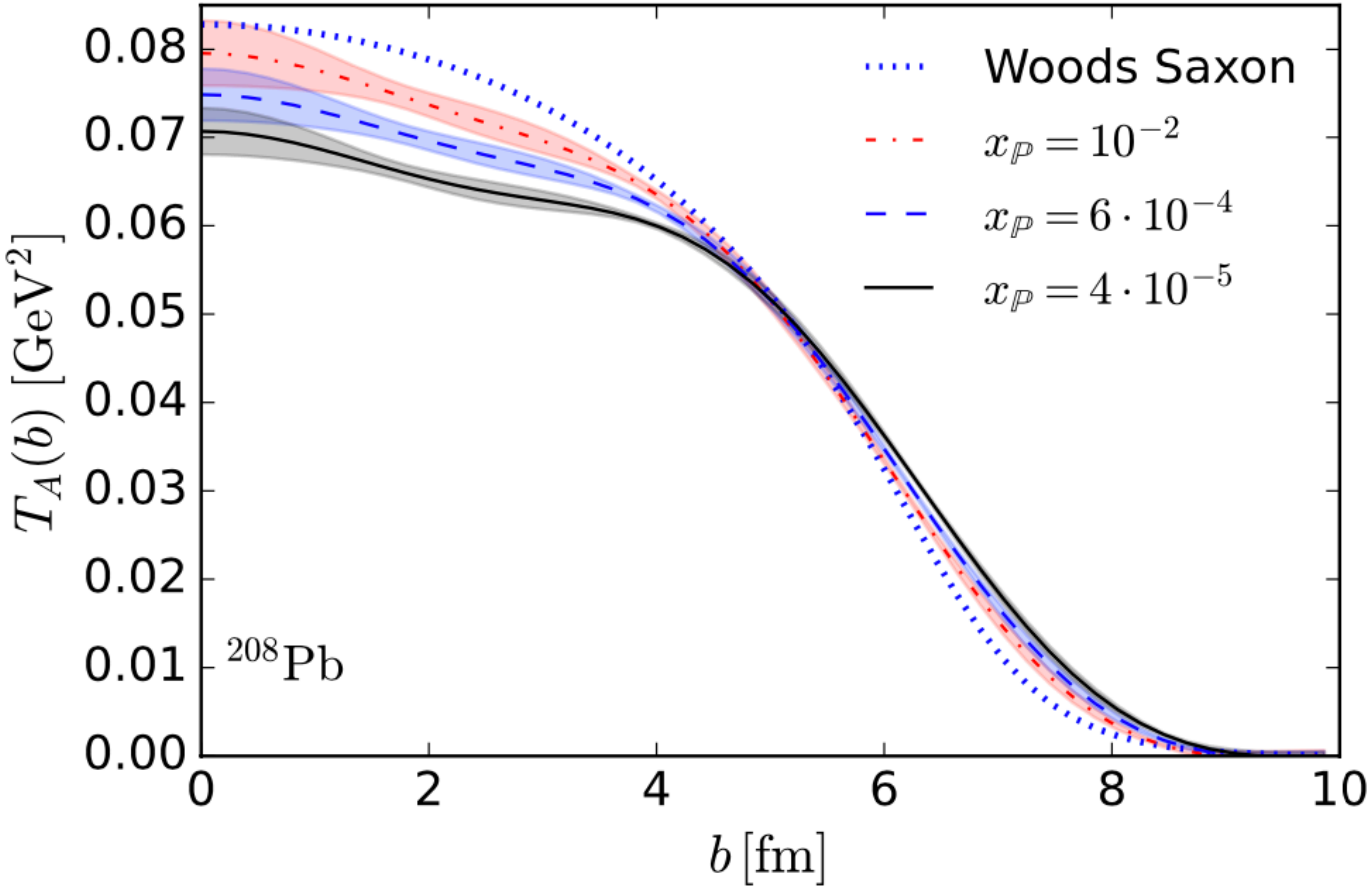
STAR Collaboration, Sci. Adv. 9, abq3903 (2023)

Saturation effects on nuclear geometry

H. Mäntysaari, F. Salazar, B. Schenke, Phys.Rev.D 106 (2022) 7, 074019

Fourier transform to coordinate space

$$T_A(b) \propto \int \Delta\, \mathrm{d}\Delta\, J_0(b\Delta)(-1)^n \sqrt{\frac{\mathrm{d}\sigma^{\gamma^*+\mathrm{Pb}\to \mathrm{J}/\psi+\mathrm{Pb}}}{\mathrm{d}|t|}},$$



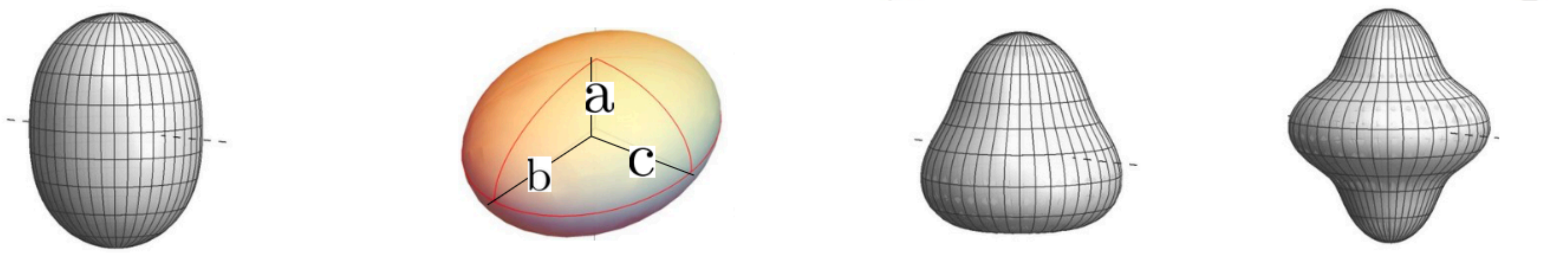
JIMWLK evolution leads to growth of the nucleus towards small x and depletion near the center (normalized so $\int d^2b T_A(b) = 208$)

Effects of deformation on diffractive cross sections

H. Mäntysaari, B. Schenke, C. Shen, W. Zhao, Phys. Rev. Lett. 131, 062301 (2023)

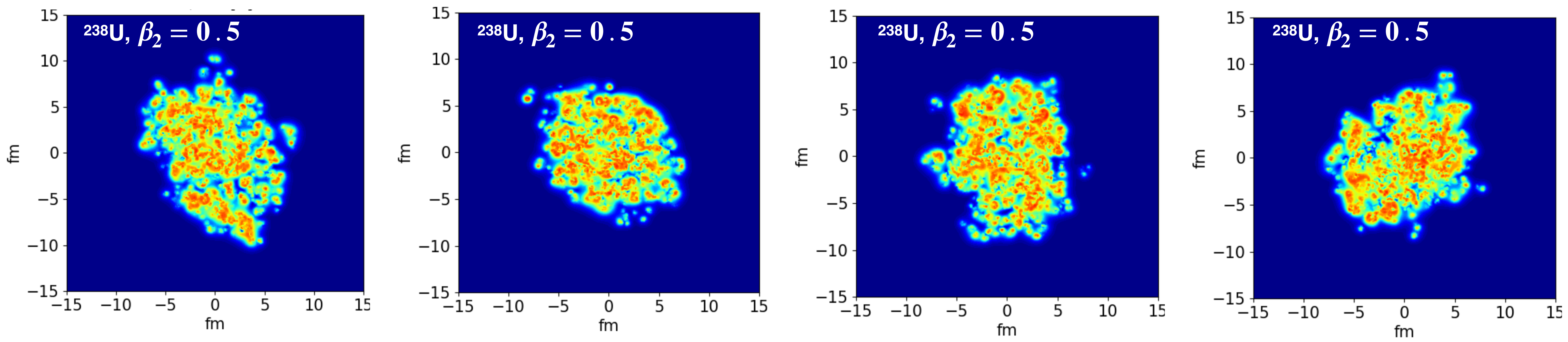
Implement deformation in the Woods-Saxon distribution:

$$\rho(r,\Theta,\Phi) \propto \frac{1}{1+\exp\left([r-R(\Theta,\Phi)]/a\right)} \; , \; R(\Theta,\Phi) = R_0\left[1+\beta_2\left(\cos\gamma Y_{20}(\Theta)+\sin\gamma Y_{22}(\Theta,\Phi)\right)+\beta_3 Y_{30}(\Theta)+\beta_4 Y_{40}(\Theta)\right]$$



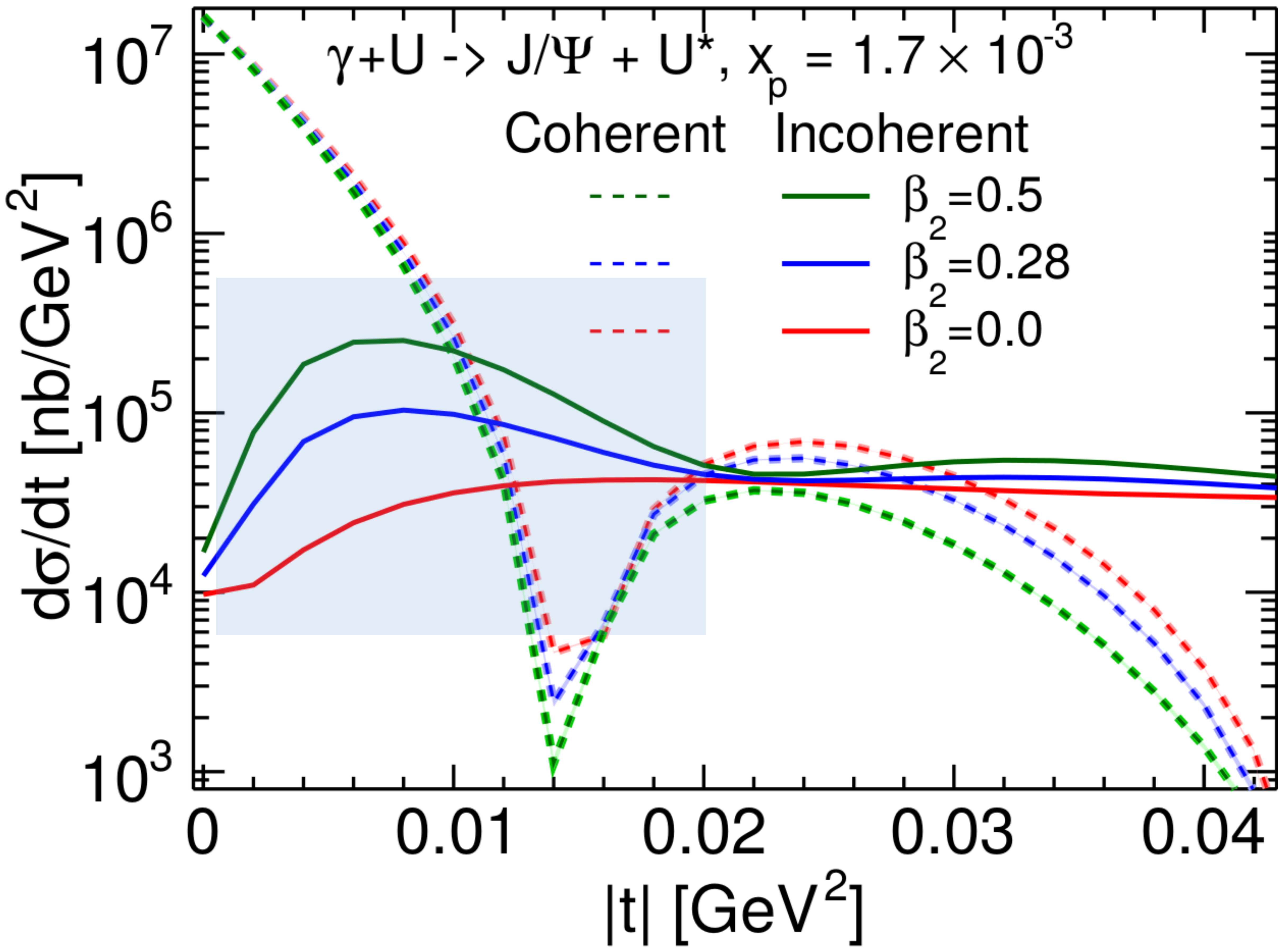
from G. Giacalone

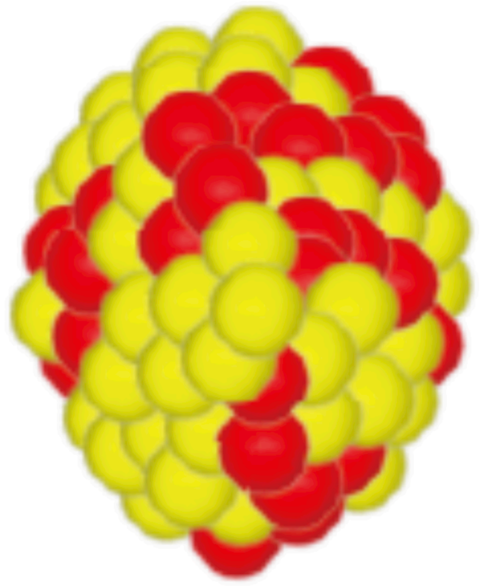
Deformed nuclei exhibit larger fluctuation in the transverse projection:



Effects of deformation on diffractive cross sections

H. Mäntysaari, B. Schenke, C. Shen, W. Zhao, Phys. Rev. Lett. 131, 062301 (2023)





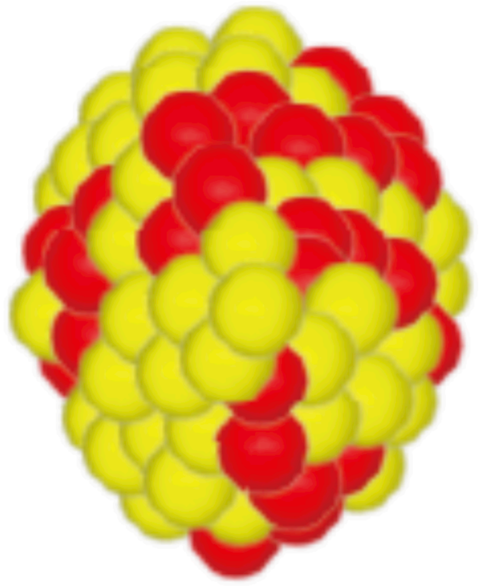
Deformation of the nucleus affects incoherent cross section at small $|t|$ (large length scales)

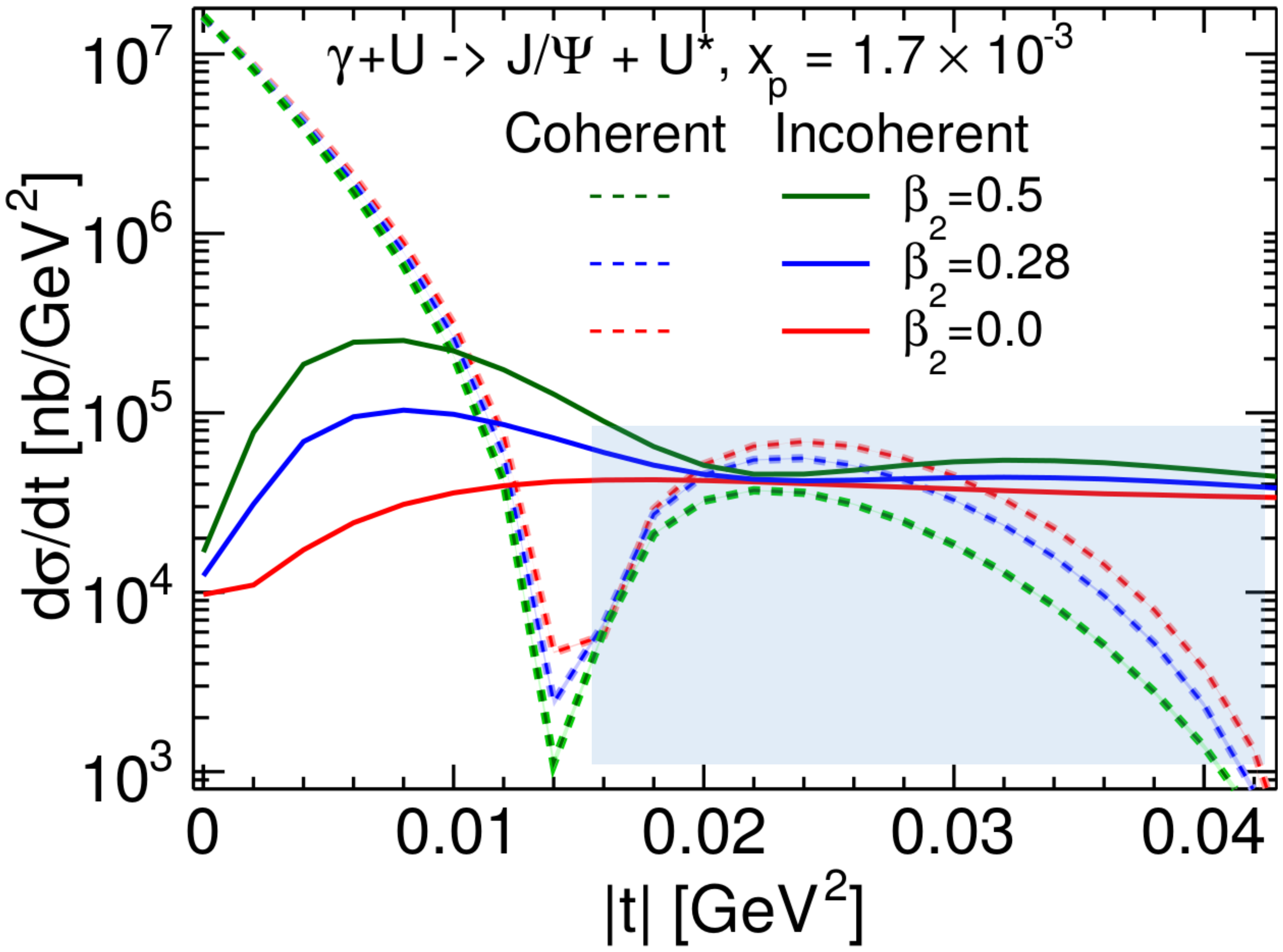
This observable provides direct information on the small x structure

$Q^2 = 0$

Effects of deformation on diffractive cross sections

H. Mäntysaari, B. Schenke, C. Shen, W. Zhao, Phys. Rev. Lett. 131, 062301 (2023)





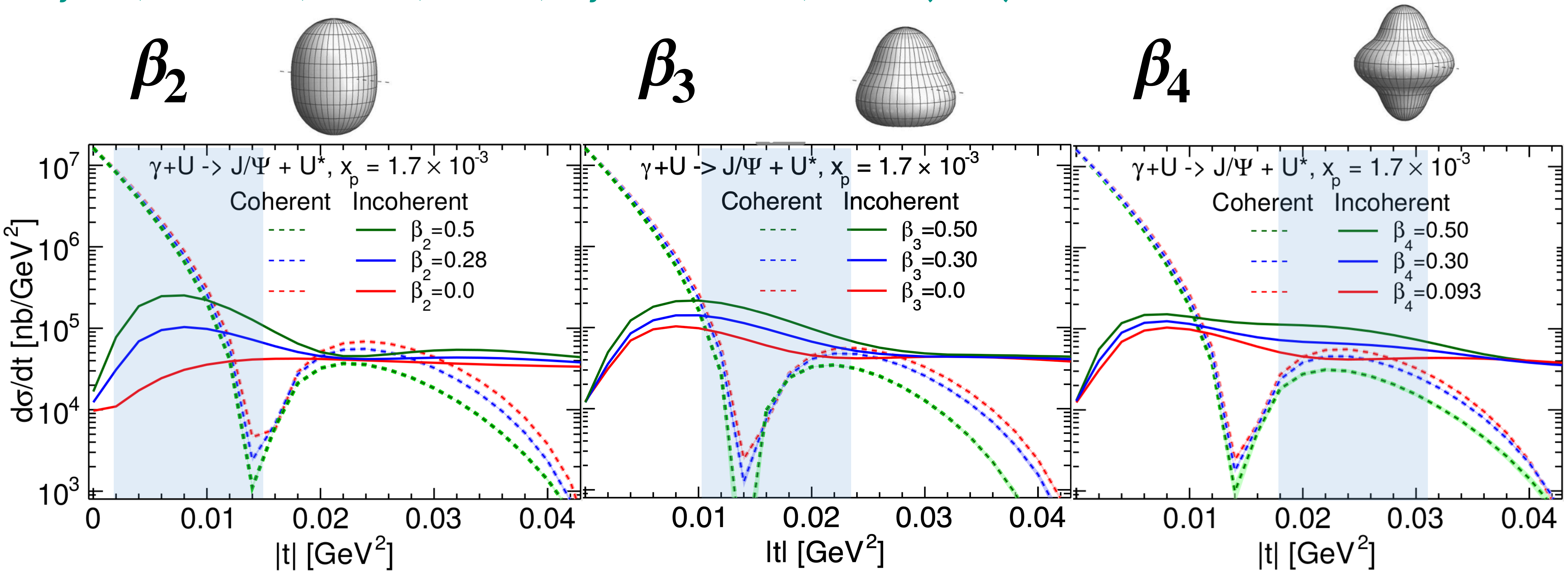
Deformation changes the shape of the average 2D projection of the nucleus

→

Modification of the coherent cross section

Effects of deformation on diffractive cross sections

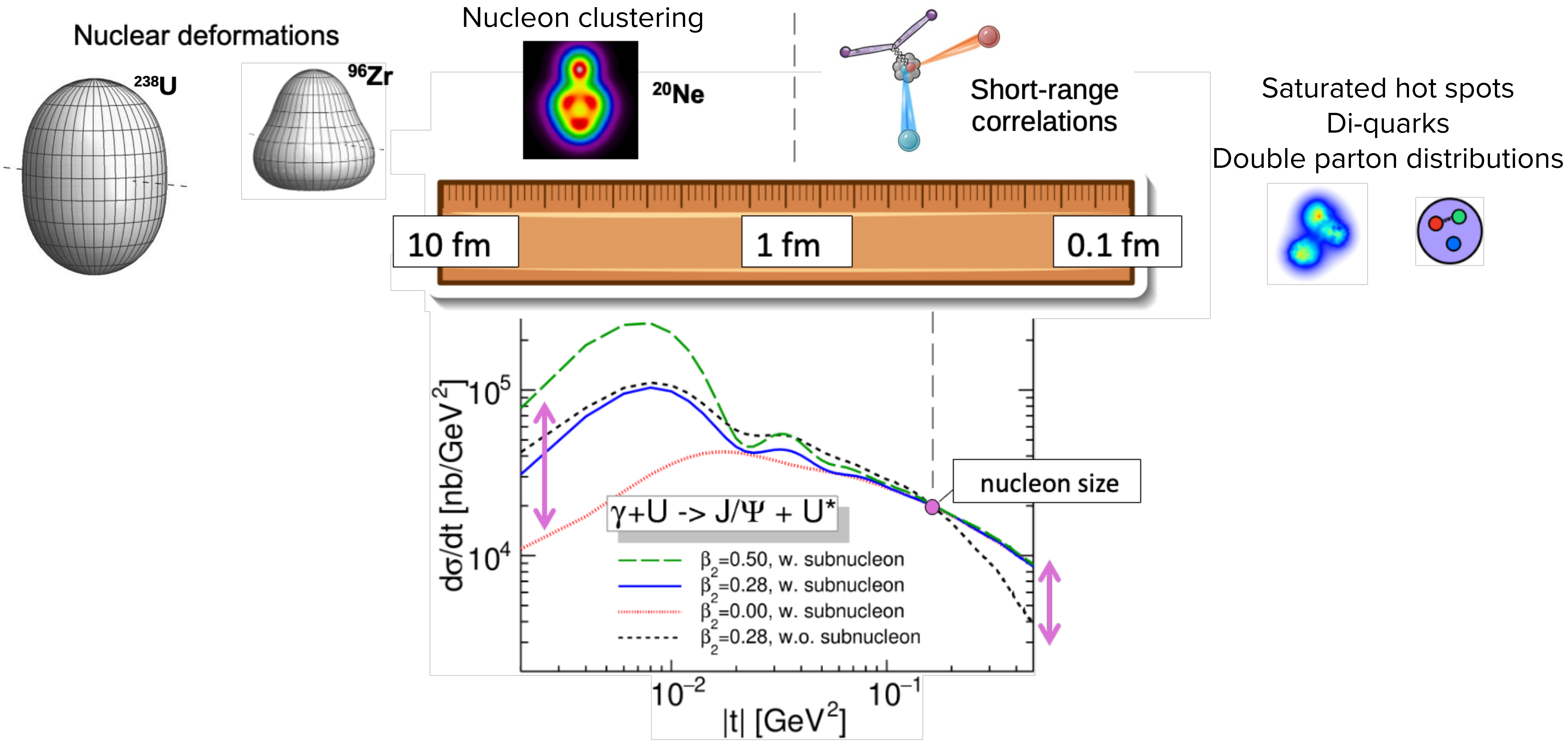
H. Mäntysaari, B. Schenke, C. Shen, W. Zhao, Phys. Rev. Lett. 131, 062301 (2023)



- β_2 , β_3 and β_4 modify fluctuations at different length scales: Change incoherent cross section in different |t| regions

Multi-scale sensitivity

H. Mäntysaari, B. Schenke, C. Shen, W. Zhao, Phys. Rev. Lett. 131, 062301 (2023)

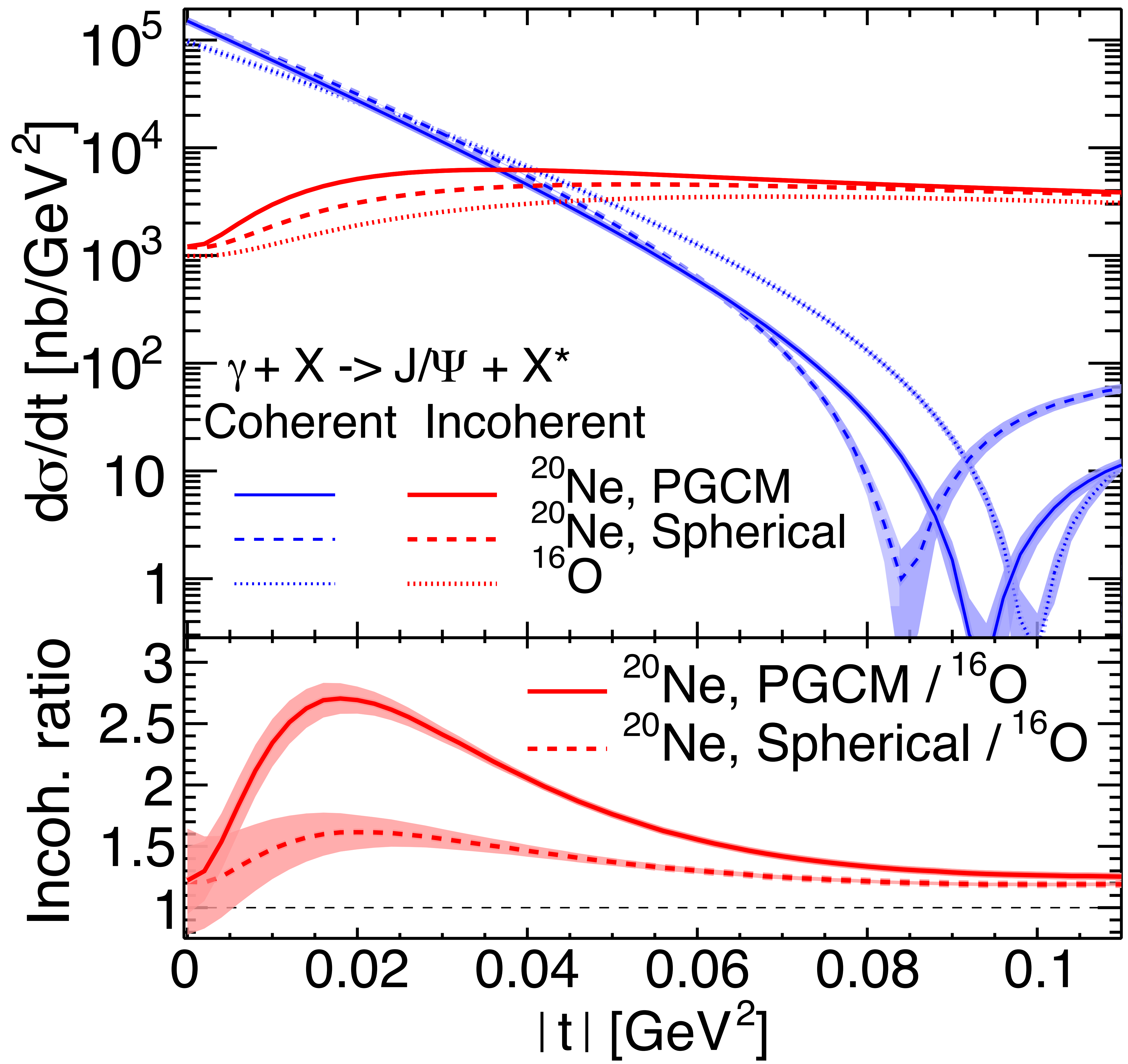


Chiral effective field theory (low-energy QCD) ⟷ **?** ⟷ **CGC effective field theory (high-energy QCD)**

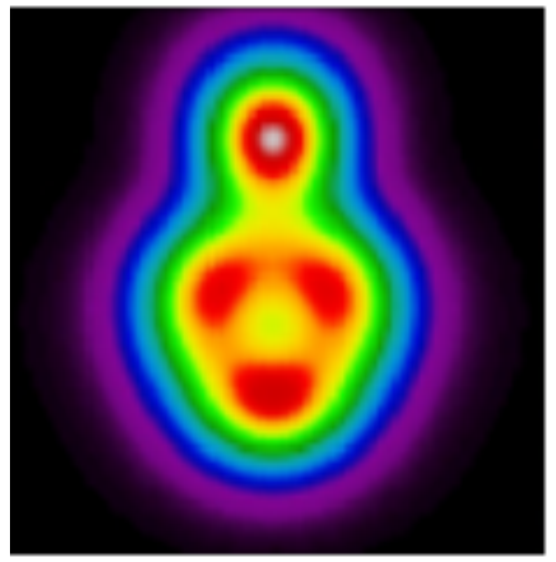
slide from G. Giacalone

Neon and Oxygen targets

H. Mäntysaari, B. Schenke, C. Shen, W. Zhao, Phys. Rev. Lett. 131, 062301 (2023)



- ^{20}Ne has a bowling pin shape that leads to an increased incoherent cross section relative to an assumed spherical (on average) neon or a spherical oxygen

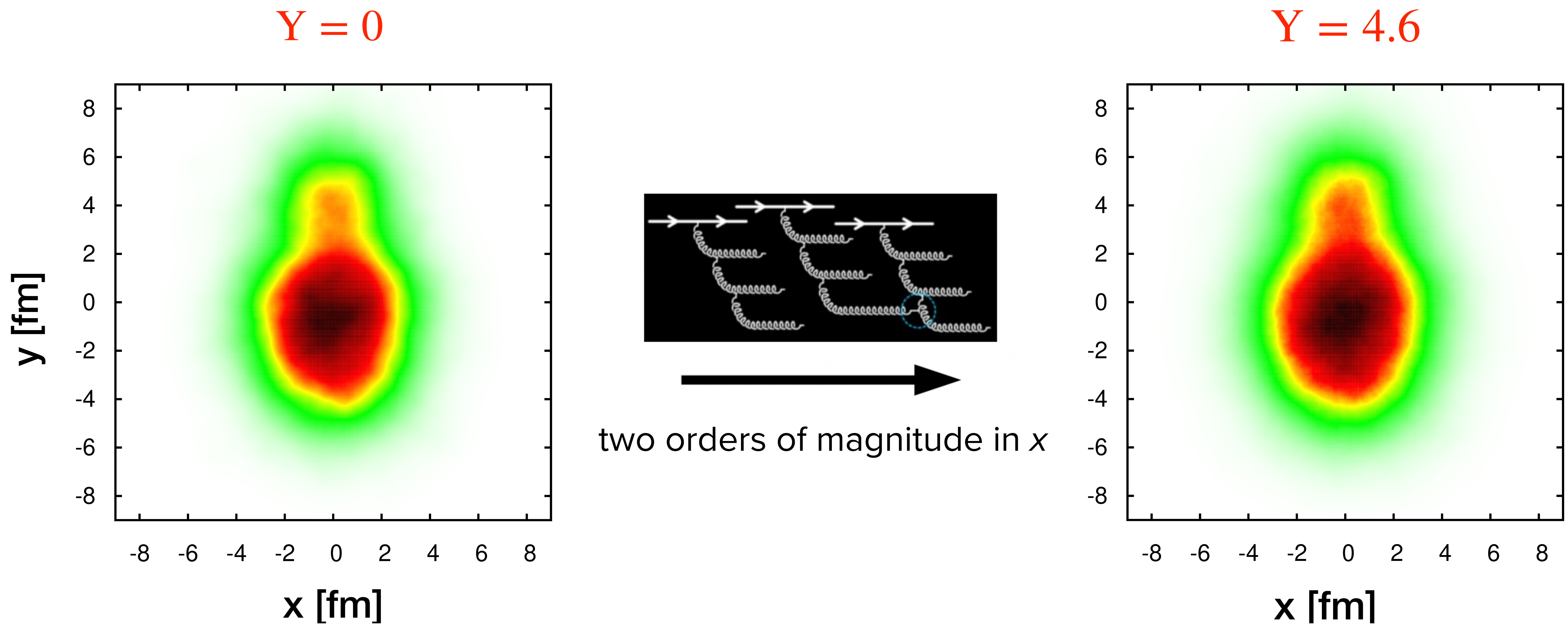


^{20}Ne

PGCM: Projected Generator Coordinate Method: B. Bally et al., "Deciphering small system collectivity with bowling-pin-shaped ^{20}Ne isotopes," in preparation (2023); Mikael Frosini, Thomas Duguet, Jean-Paul Ebran, Benjamin Bally, Tobias Mongelli, Toma´s R. Rodrıguez, Robert Roth, and Vittorio Soma, Eur. Phys. J. A 58, 63 (2022)

Neon - JIMWLK evolution

G. Giacalone, B. Schenke, S. Schlichting, P. Singh

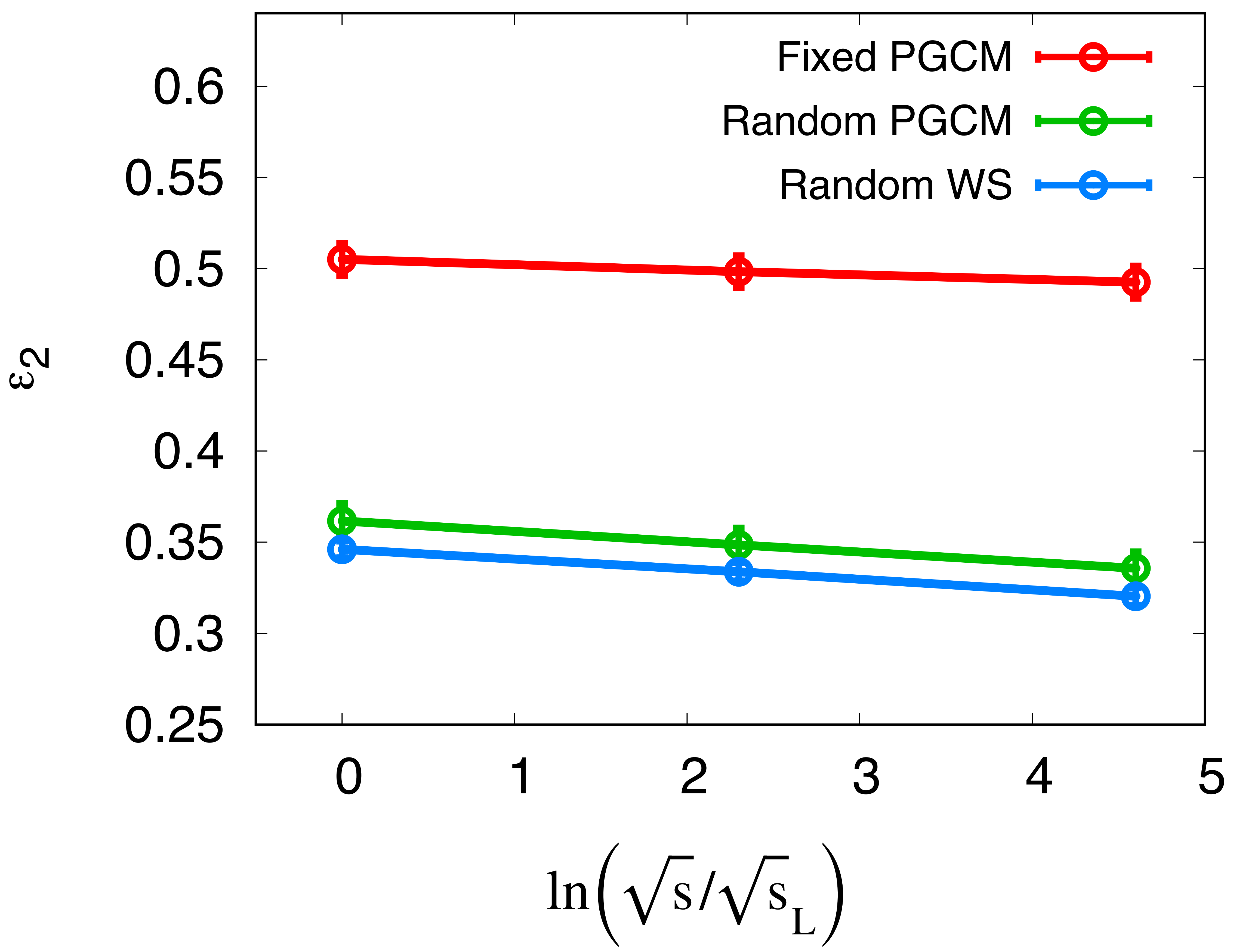


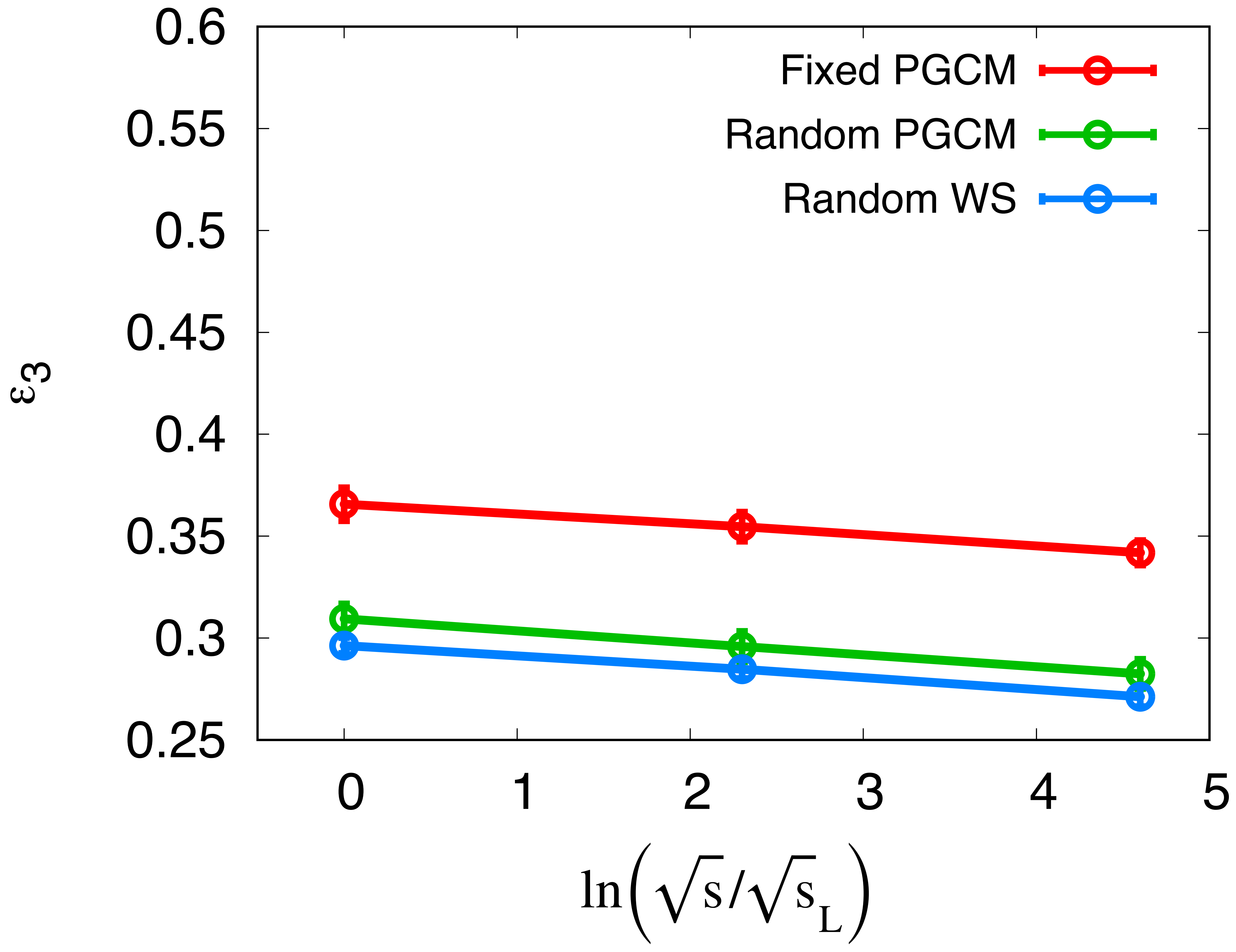
- Small-x evolution does not melt the bowling pin shape

Neon+Neon collisions - JIMWLK evolution

G. Giacalone, B. Schenke, S. Schlichting, P. Singh

- After the collision at different energies (x), measure the spatial eccentricities



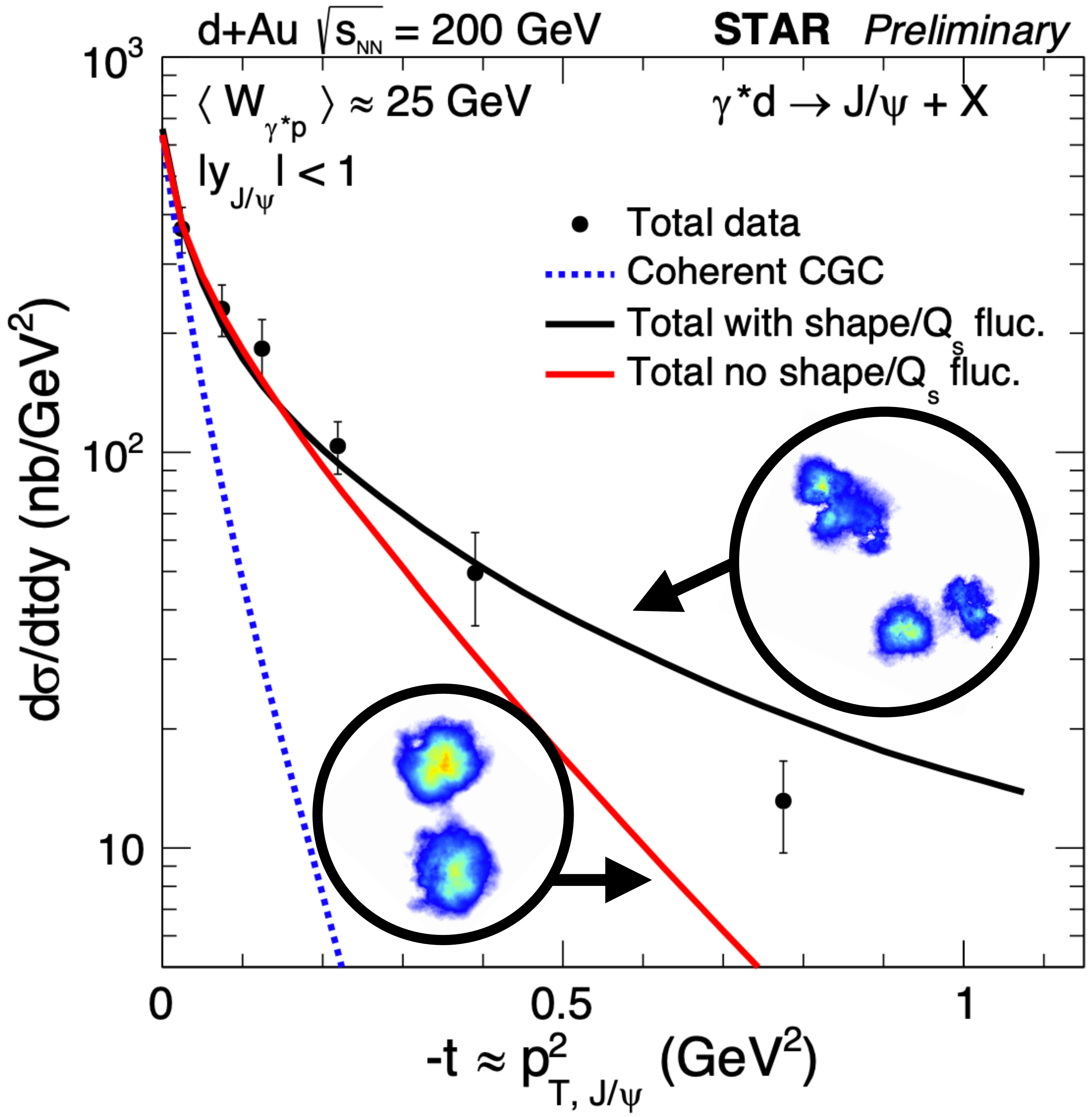


PGCM: Projected Generator Coordinate Method

- Expected reduction - smoother distributions, but no large change

Photoproduction of J/ψ in d+Au collisions at STAR

H. Mäntysaari, B. Schenke, Phys. Rev. C101, 015203 (2020)



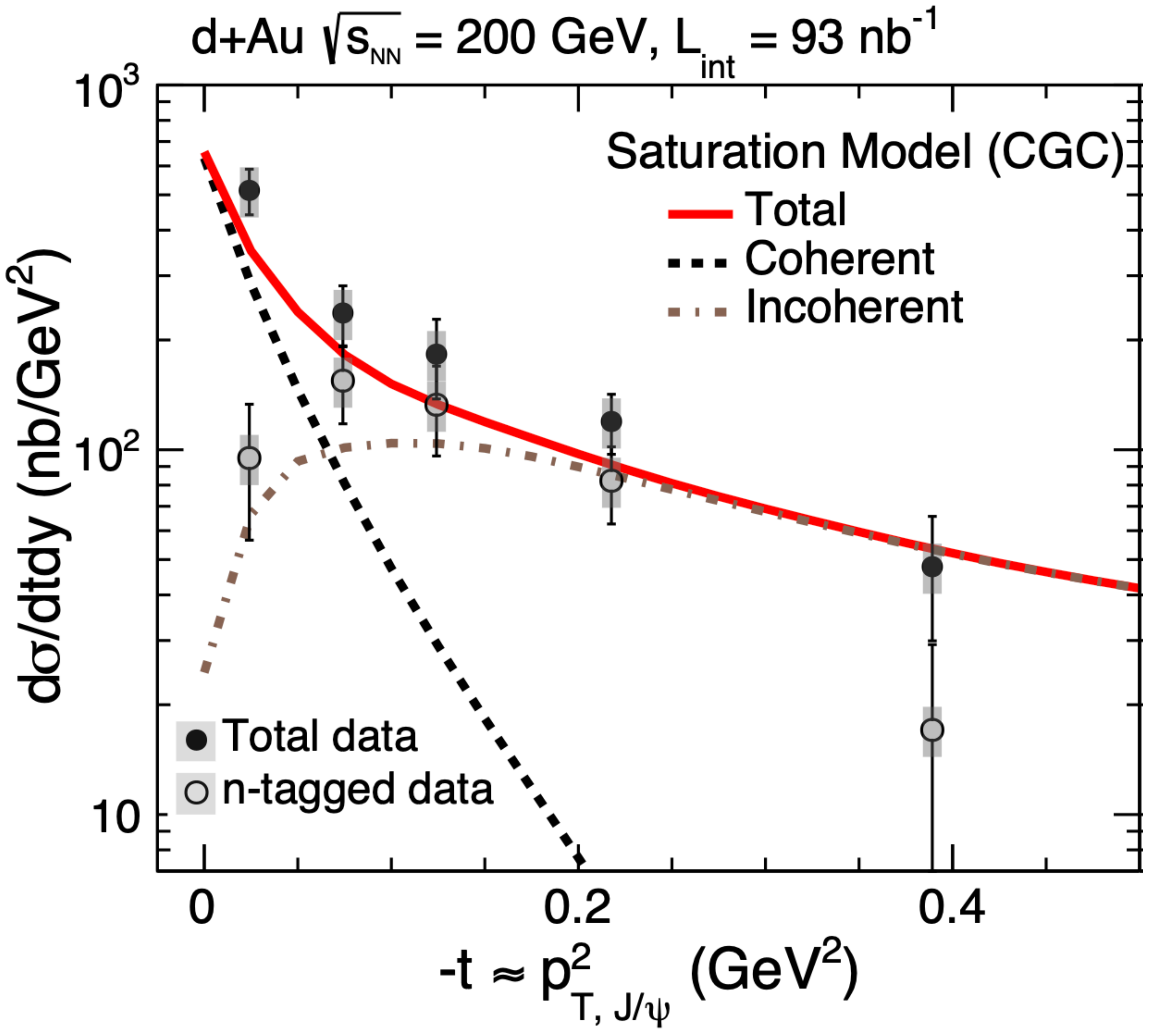
Substructure: large effect on incoherent at $|t| \gtrsim 0.25\mathrm{GeV}^2$

STAR data favors substructure

STAR Collaboration at Hard Probes 2020
PoS **HardProbes2020 (2021) 100; arXiv:2009.04860**

Photoproduction of J/ψ in d+Au collisions at STAR

H. Mäntysaari, B. Schenke, Phys. Rev. C101, 015203 (2020)

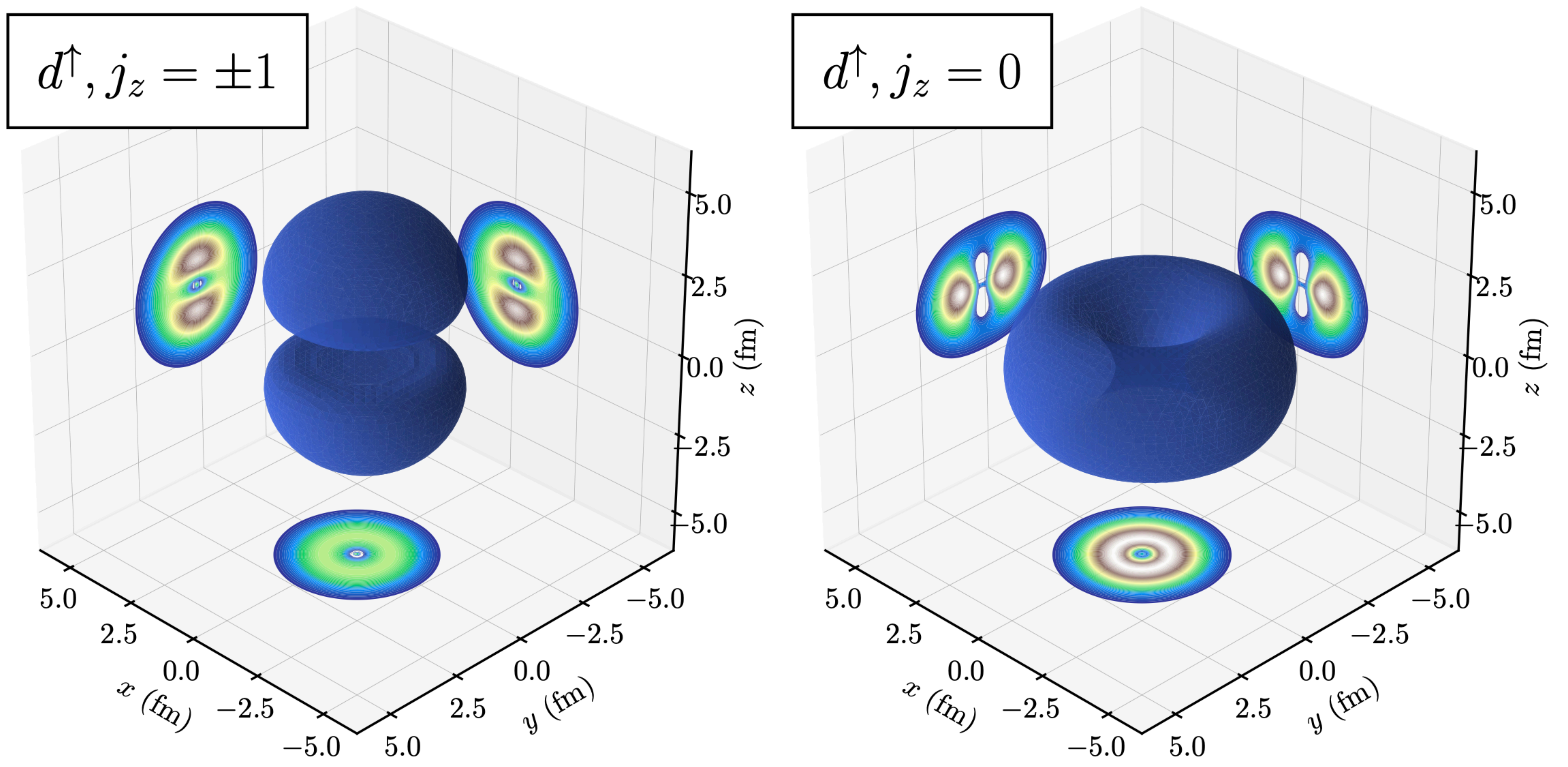


n-tagged results can be compared to incoherent cross section

STAR Collaboration, Phys. Rev. Lett. 128, 122303, (2022) e-Print: 2109.07625

Polarized Deuteron

H. Mäntysaari, F. Salazar, B. Schenke, C. Shen, W. Zhao, Phys.Lett.B 858 (2024) 139053



Polarized Deuteron

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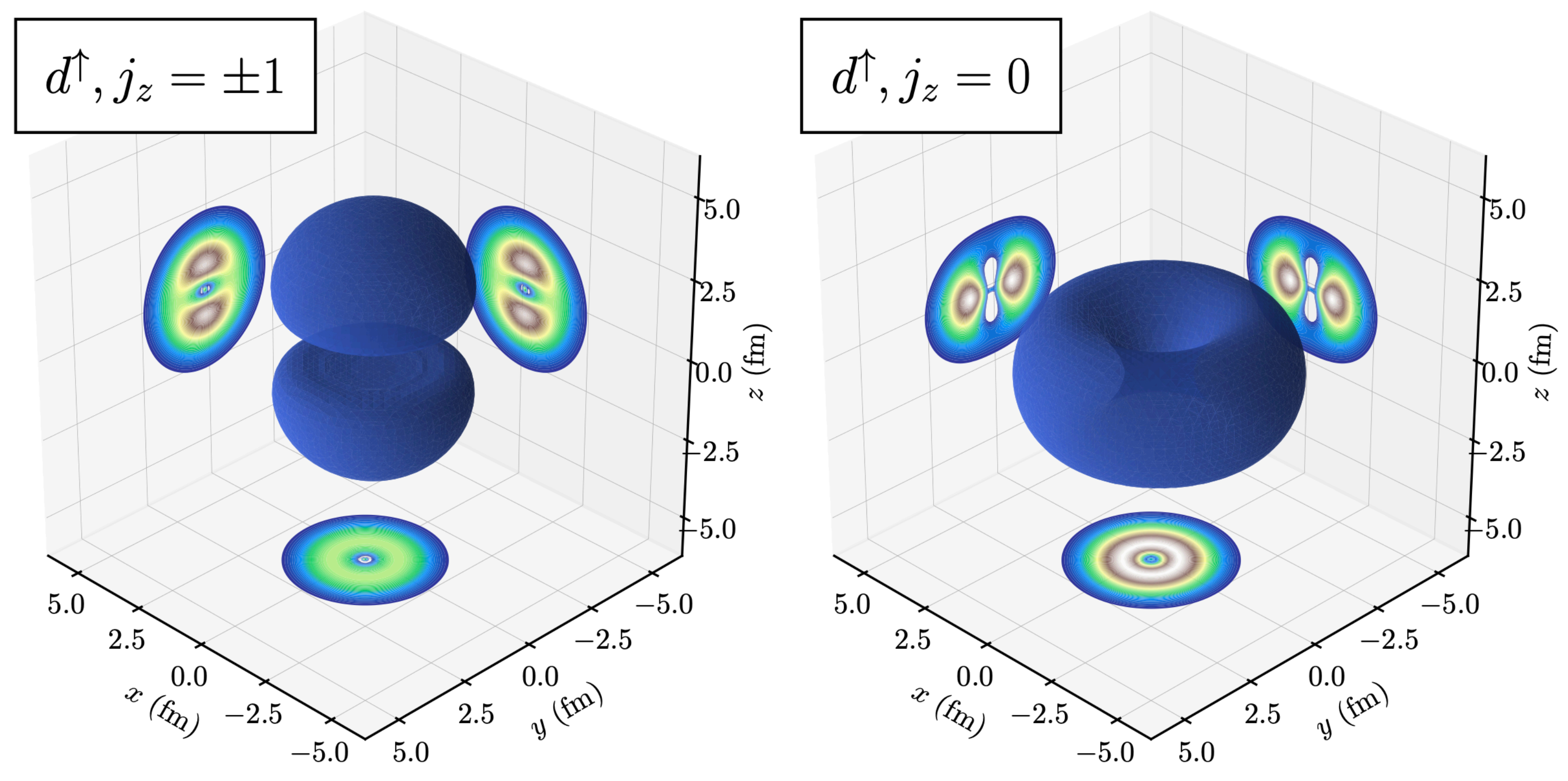
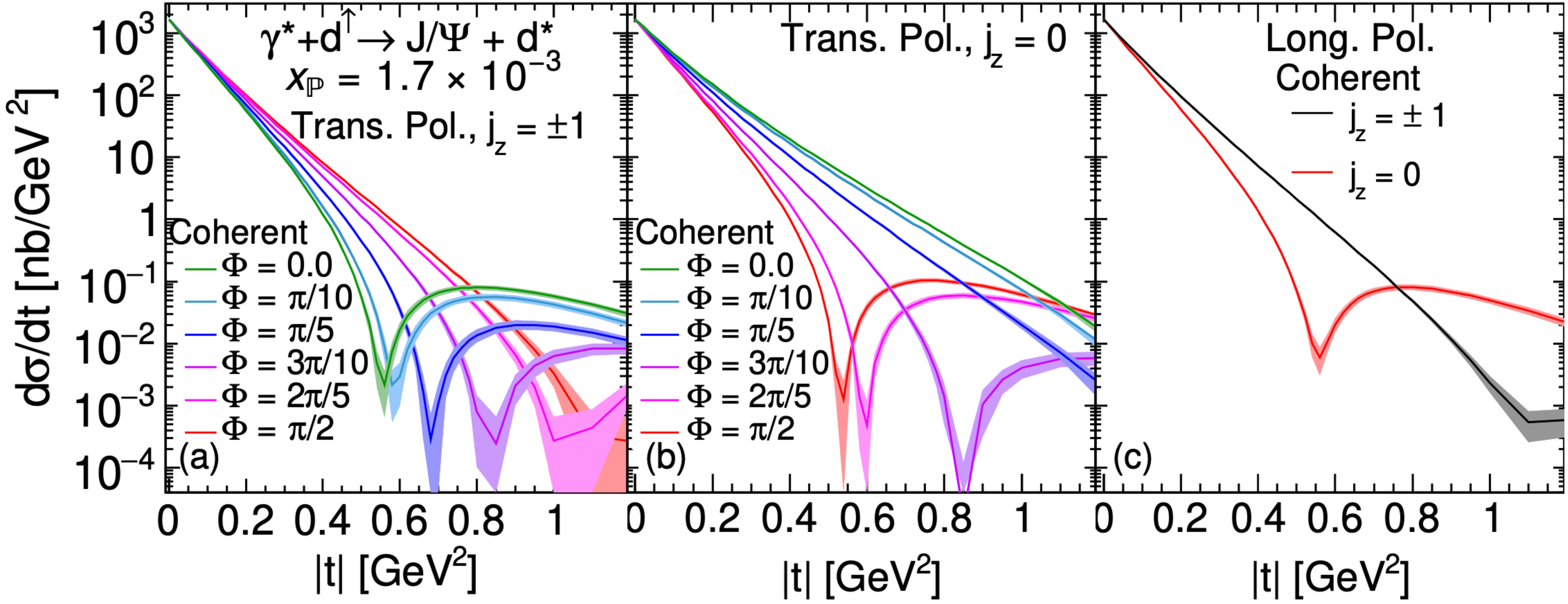
Phys.Lett.B 858 (2024) 139053





Polarized Deuteron

H. Mäntysaari, F. Salazar, B. Schenke, C. Shen, W. Zhao, Phys.Lett.B 858 (2024) 139053

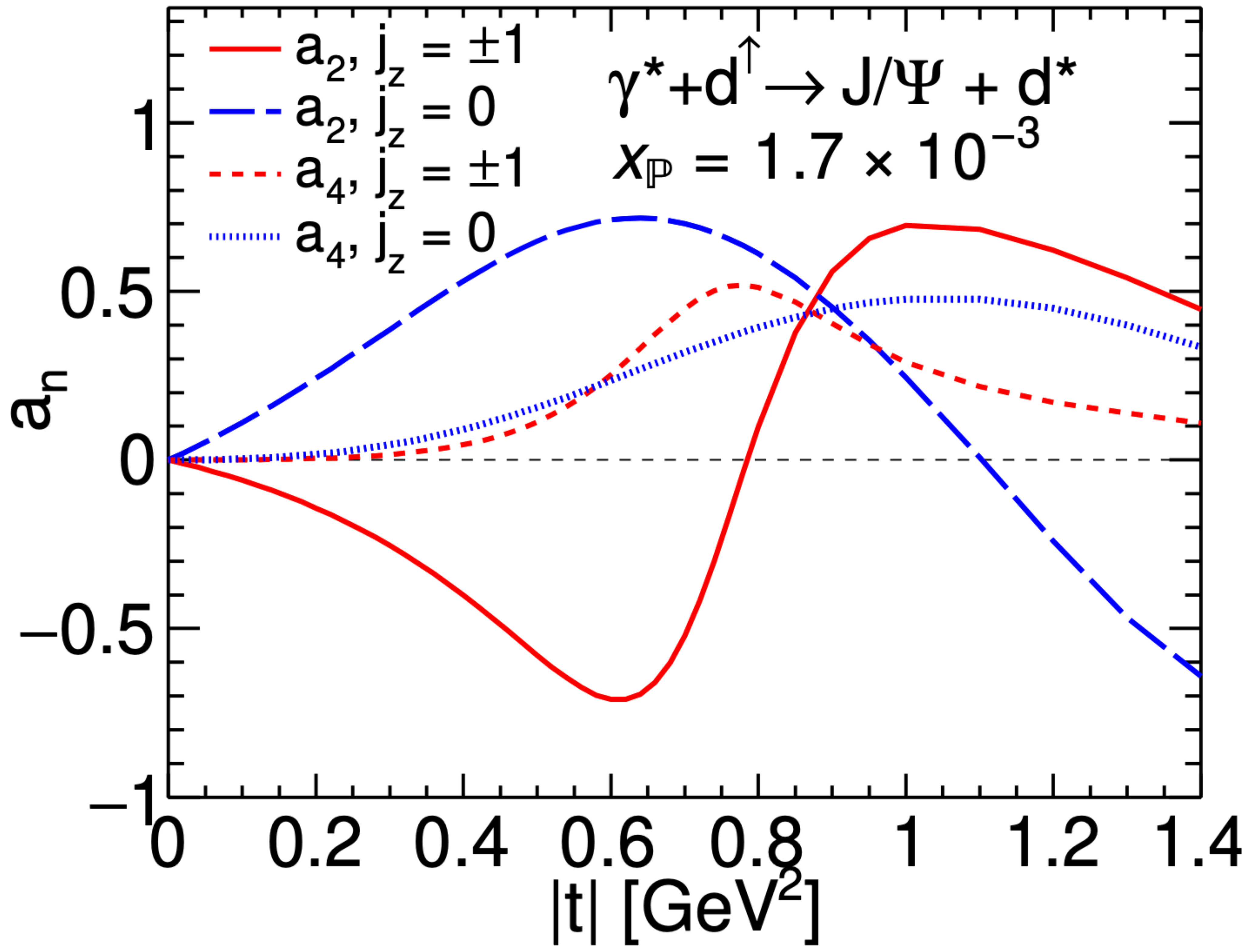


FIG. 4. Real parts of the second (a_2) and the forth order (a_4) coefficients as functions of $|t|$ in transverse polarized $e + d$ collisions.

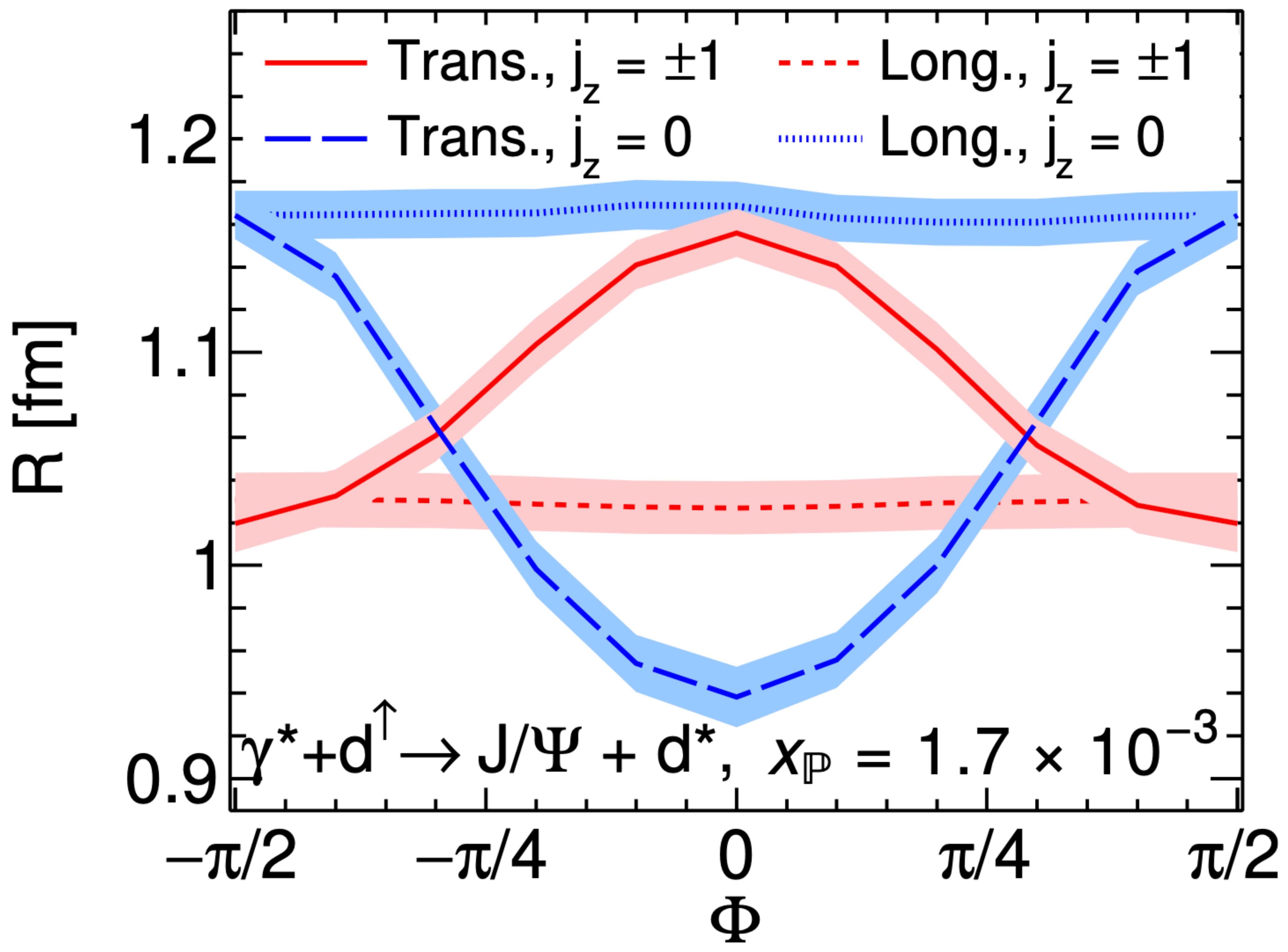
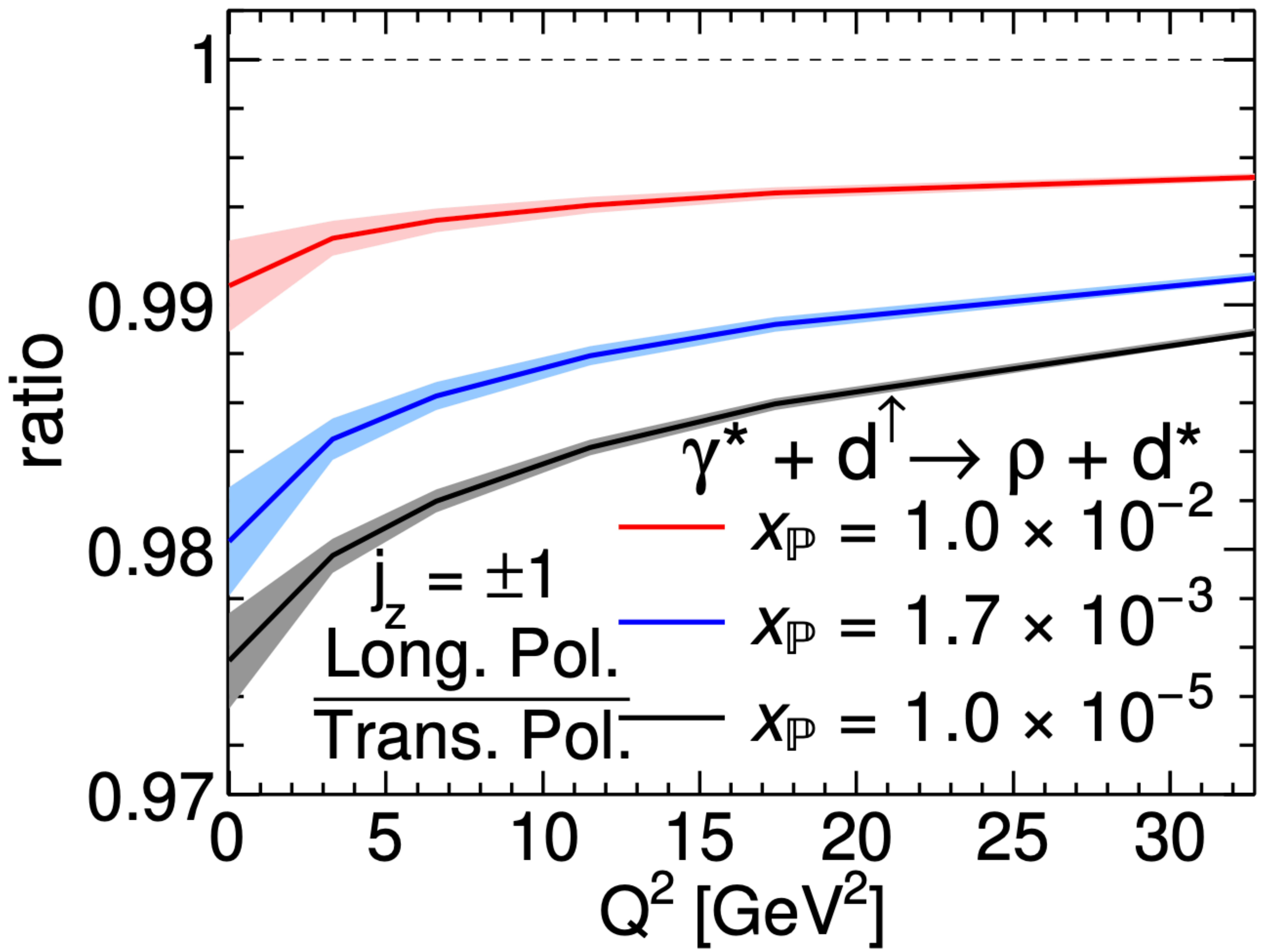


FIG. 5. The effective transverse radius as a function of the Φ angle defined relative to the polarization direction of transverse polarization.

Polarized Deuteron

H. Mäntysaari, F. Salazar, B. Schenke, C. Shen, W. Zhao, Phys.Lett.B 858 (2024) 139053



- Fixing the polarization allows to fix the orientation relative to the beam axis (for Q^2=0)
- This allows for testing saturation effects
- Small difference in coherent cross section at $t = 0$ for deuteron, as expected

Summary

- Diffractive vector meson production in UPCs: Complementary way to access nuclear geometry
- Differential incoherent diffractive cross section sensitive to deformation at different length scales
- Difference between ^{20}Ne and ^{16}O up to factor of 2-3
- Deuteron data compatible with similar subnucleon fluctuations as observed in proton targets
- Polarized deuteron: Spatial stucture of polarized wave function^2

BACKUP

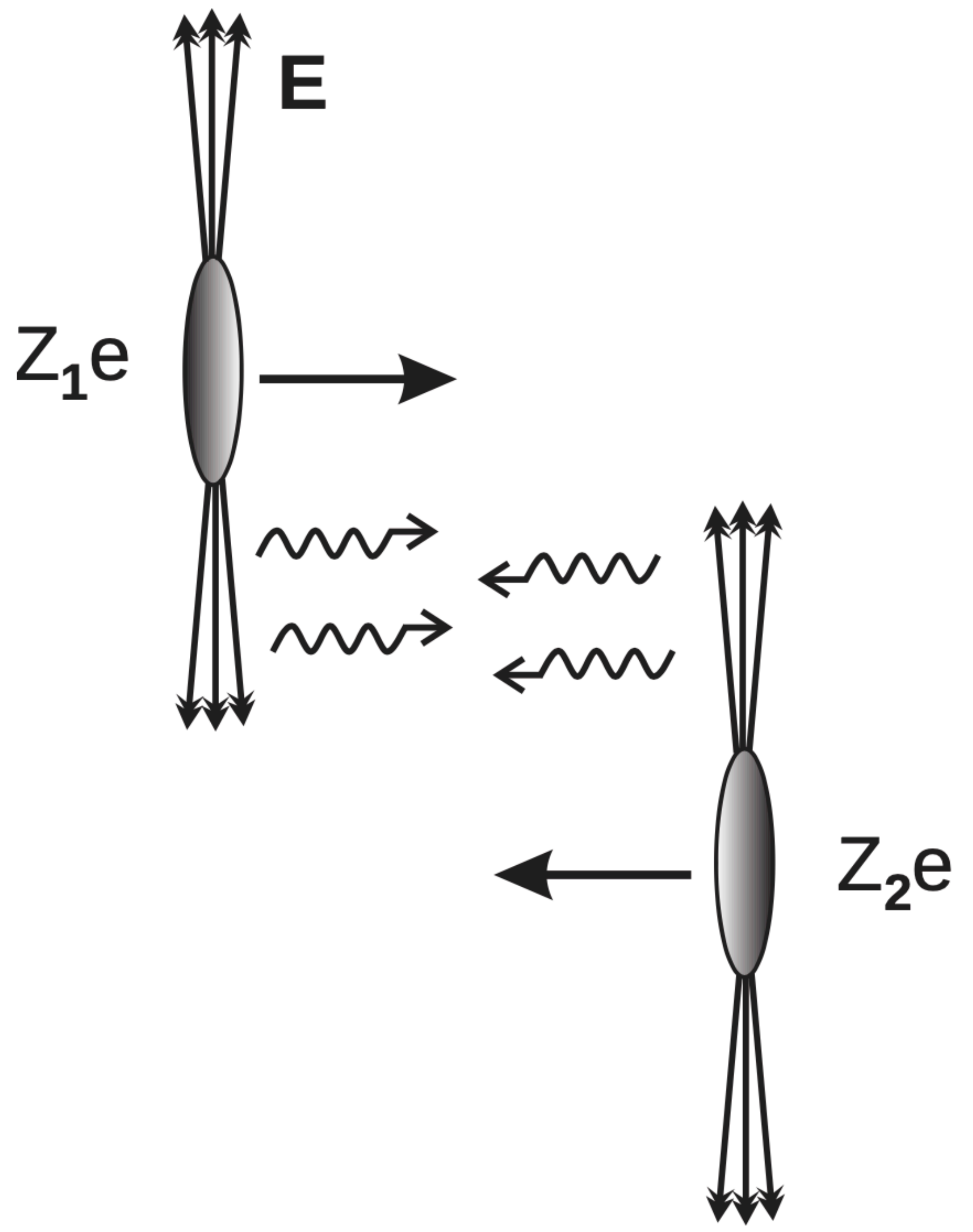
Interference effects

C. A. Bertulani, S. R. Klein and J. Nystrand, Ann. Rev. Nucl. Part. Sci. 55 (2005) 271

Interference is important for the differential cross-section in A+A, especially at midrapidity. There

$$\frac{d\sigma}{d|t|} = \frac{1}{16\pi}\int d^2\mathbf{B}\,|A_1 - A_2|^2\,\theta(|\mathbf{B}| - 2R_A)$$

Interference is destructive in A+A because of negative parity of the VM

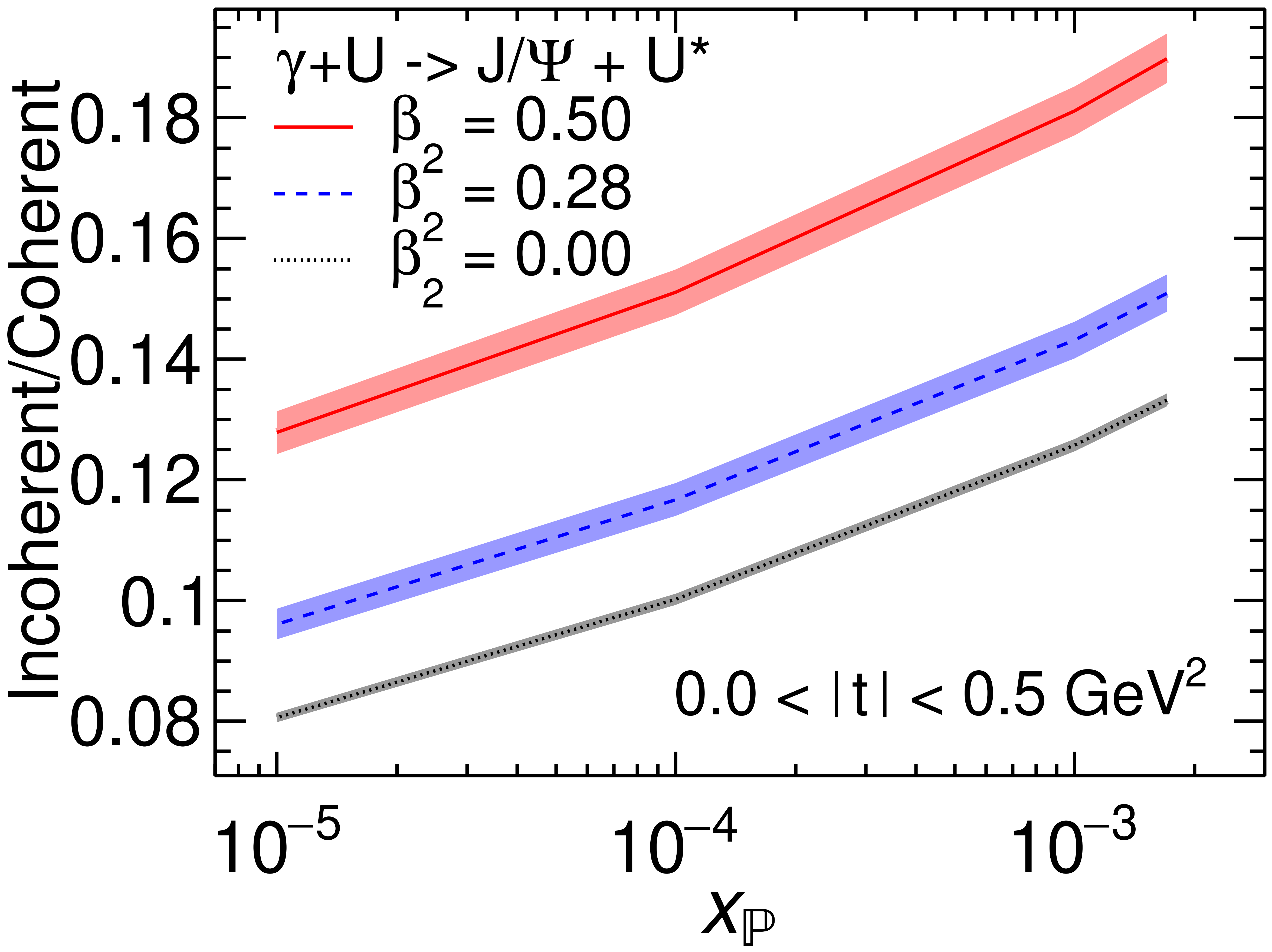


$$\left.\frac{d\sigma^{A_1+A_2\to V+A_1+A_2}}{d|t|\,dy}\right|_{y=0} = 2\int d^2\mathbf{B}\,n(\omega,|\mathbf{B}|)\frac{d\sigma^{\gamma+A\to V+A}}{d|t|}[1-\cos(\mathbf{\Delta}\cdot\mathbf{B})]\,\theta(|\mathbf{B}|-2R_A)$$

with $t = -\mathbf{\Delta}^2$

Towards smaller *x*

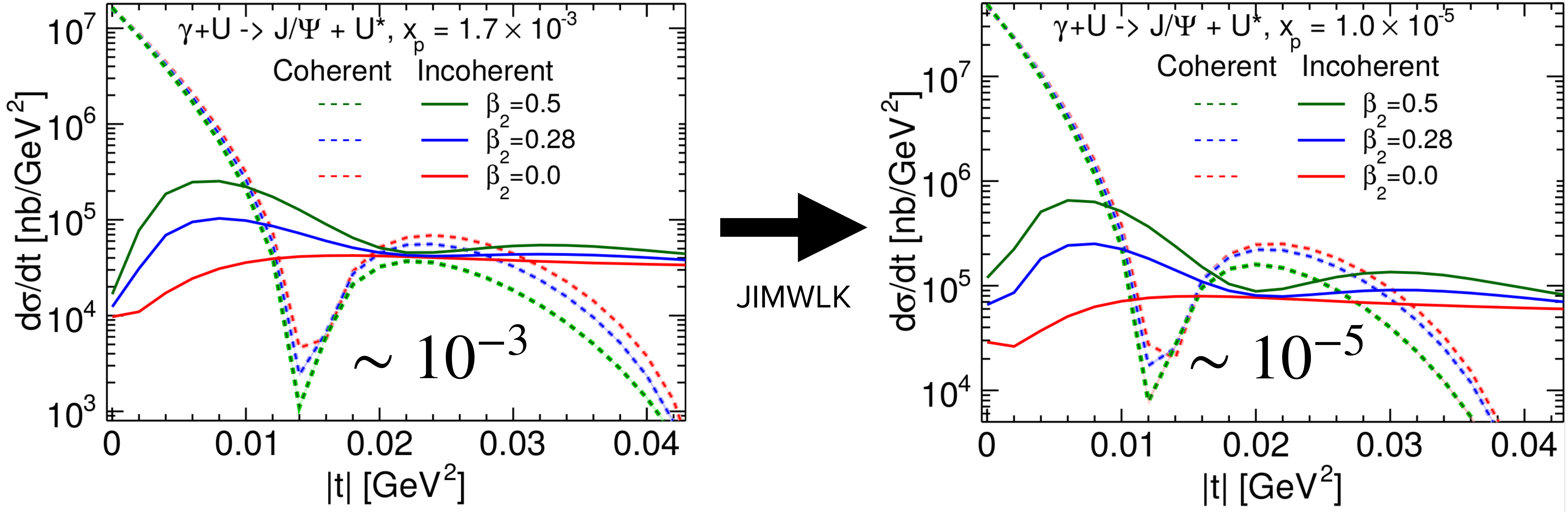
H. Mäntysaari, B. Schenke, C. Shen, W. Zhao, Phys. Rev. Lett. 131, 062301 (2023)



- JIMWLK evolution to smaller *x*
- Both cross sections increase
- Ratio incoherent/coherent decreases because fluctuations are reduced (nucleus becomes smoother)
- Difference between different β_2 does not decrease noticeably in this x range
- Is there a large enough x range we can cover at the EIC (at least 10^{-3} - 10^{-2})?

Towards smaller *x*: Do deformation effects survive?

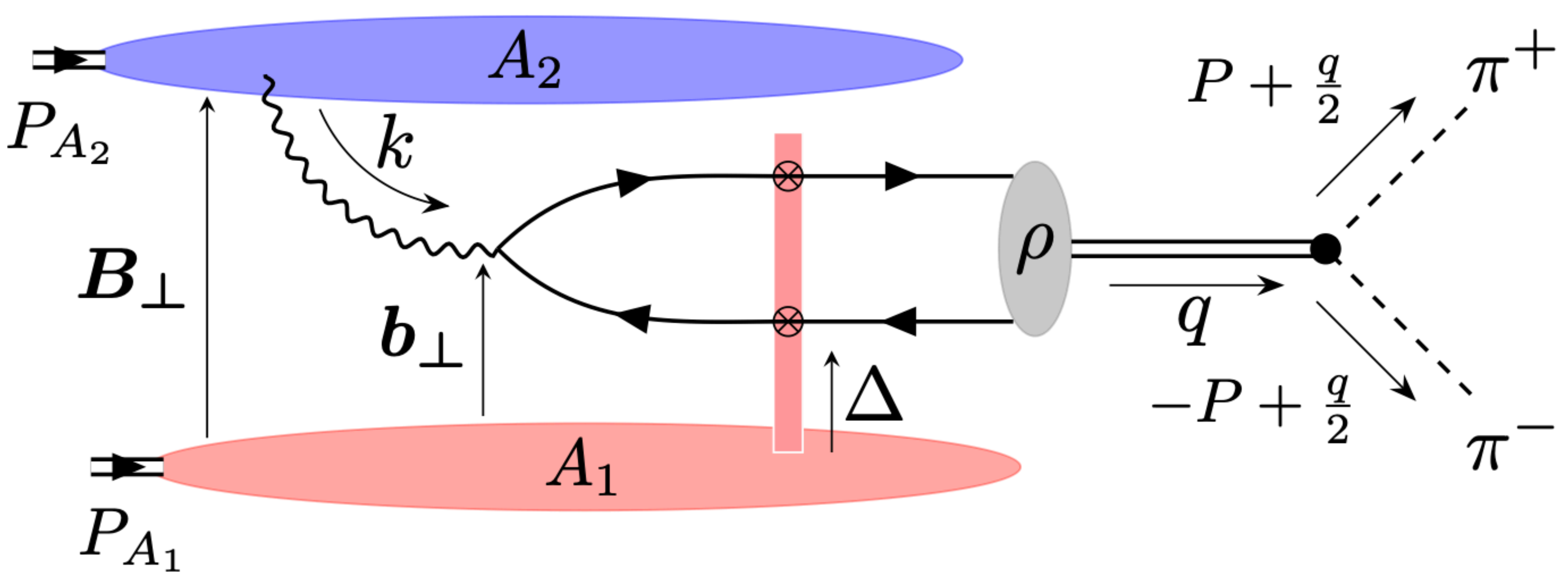
H. Mäntysaari, B. Schenke, C. Shen, W. Zhao, in progress

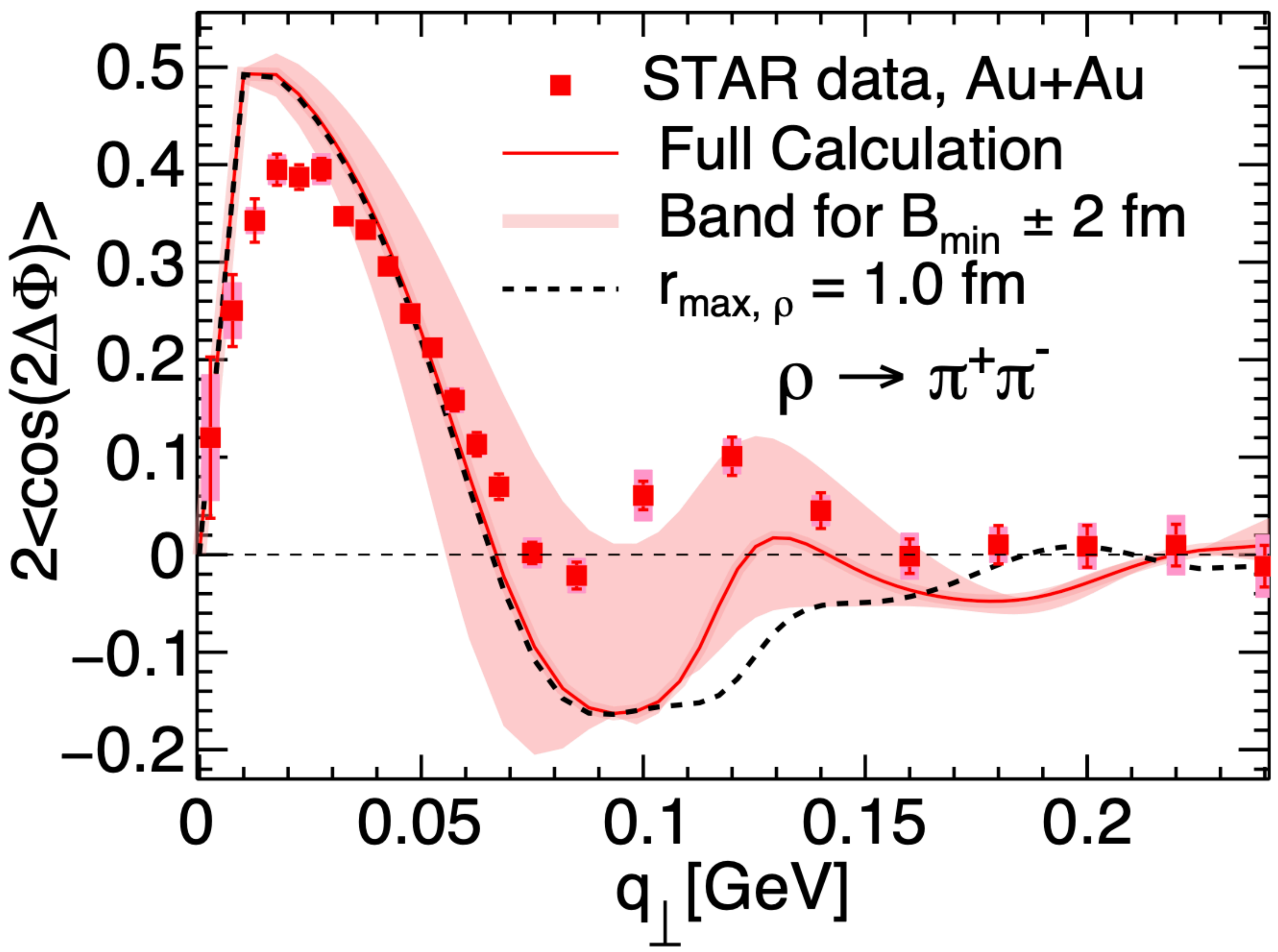


Some changes in the cross section, but deformation effects survive

Angular anisotropies: Interference effects - ρ production

Heikki Mäntysaari, Farid Salazar, Björn Schenke, Chun Shen, Wenbin Zhao, arXiv:2310.15300





$$\frac{d\sigma^{\rho\to\pi^+\pi^-(\phi\to K^+K^-)}}{d^2\mathbf{P}_\perp d^2\mathbf{q}_\perp dy_1 dy_2} = \frac{1}{4(2\pi)^3}\frac{P_\perp^2 f^2}{(Q^2 - M_V^2)^2 + M_V^2\Gamma^2}\left\{C_0(x_1, x_2, |\mathbf{q}_\perp|) + C_2(x_1, x_2, |\mathbf{q}_\perp|)\cos(2(\phi_{\mathbf{P}_\perp} - \phi_{\mathbf{q}_\perp}))\right\}$$

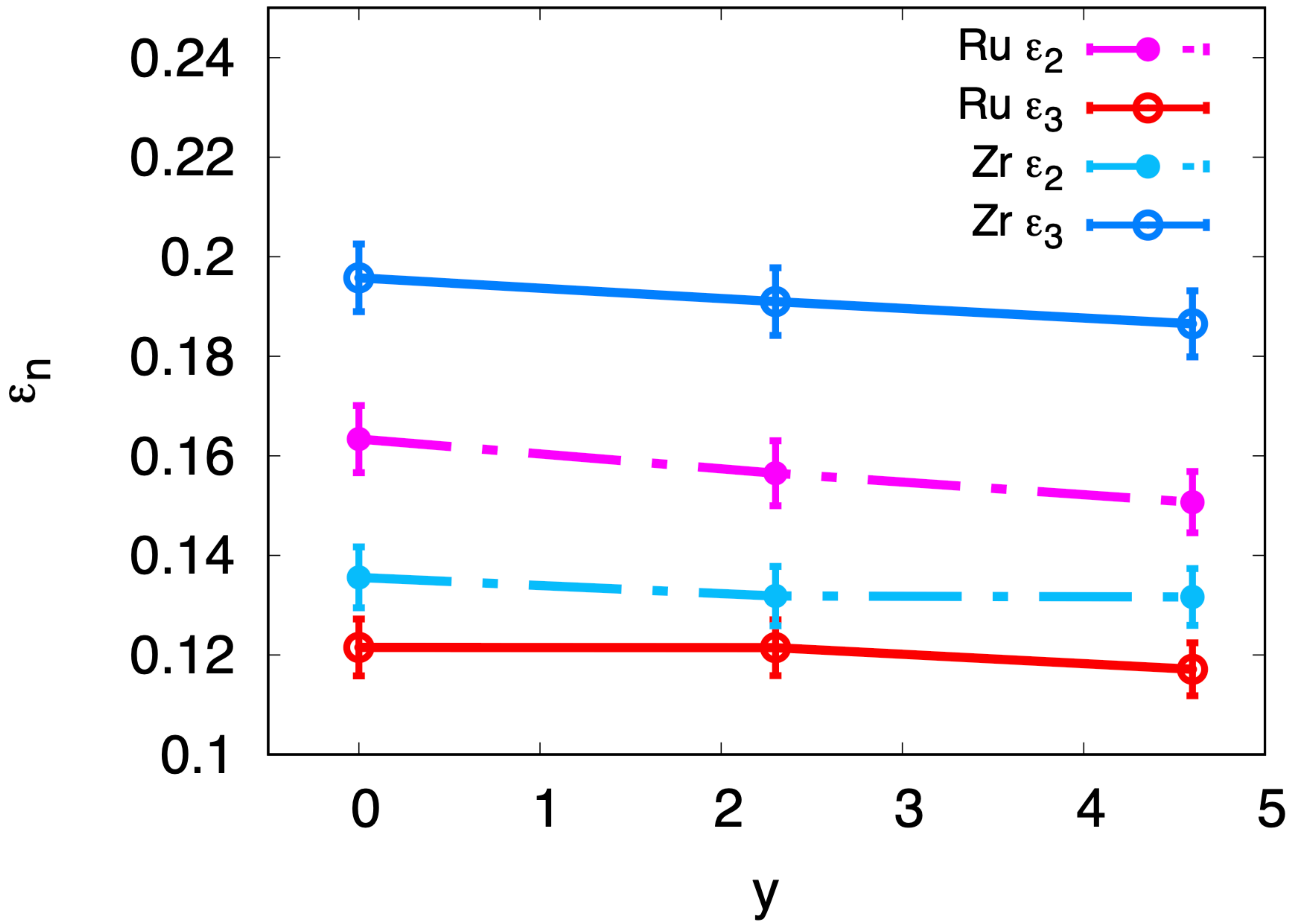
where

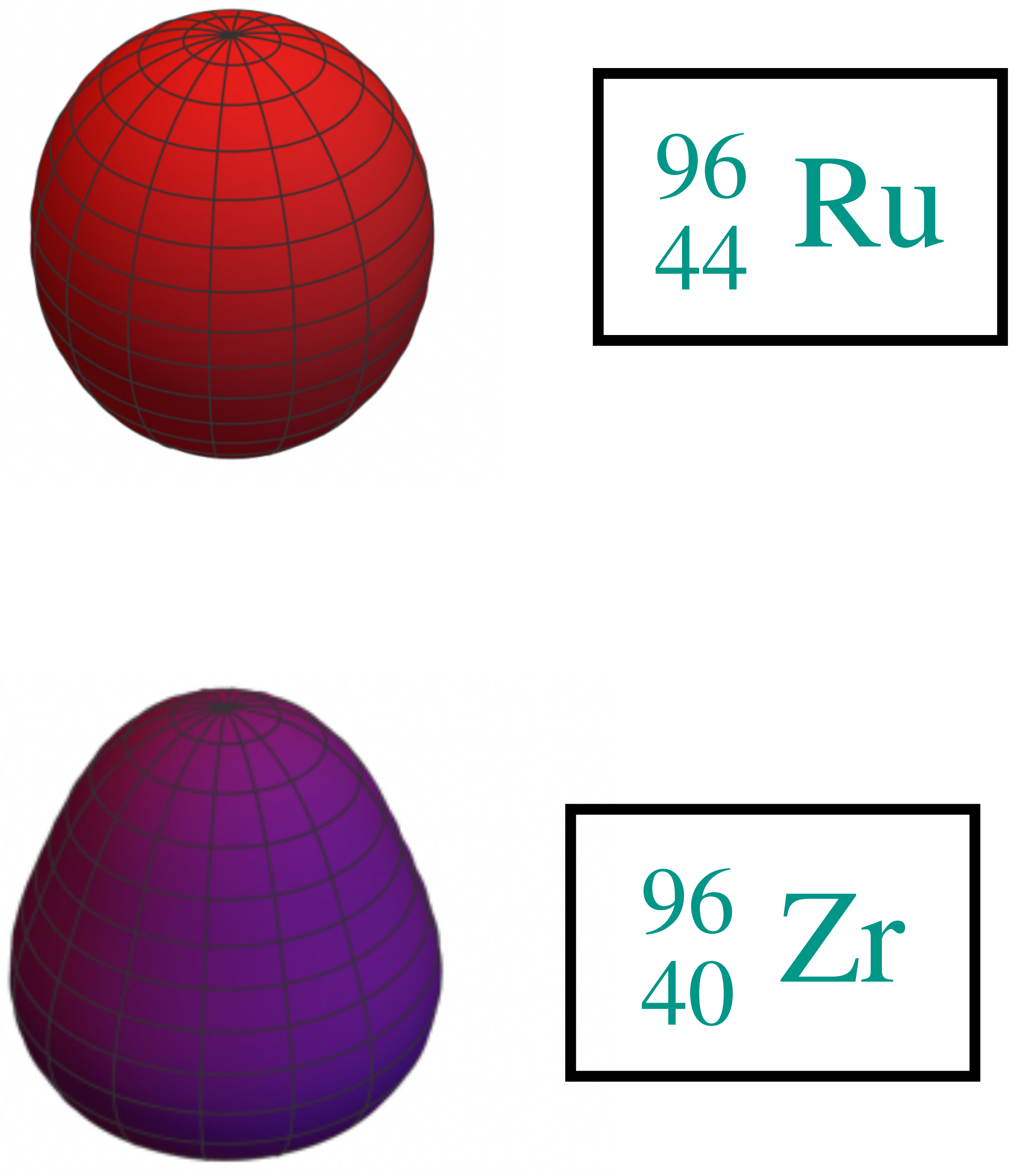
$$C_0(x_1, x_2, |\mathbf{q}_\perp|) = \left\langle \int d^2\mathbf{B}_\perp \mathcal{M}^i(x_1, x_2, \mathbf{q}_\perp, \mathbf{B}_\perp)\mathcal{M}^{\dagger,i}(x_1, x_2, \mathbf{q}_\perp, \mathbf{B}_\perp)\Theta(|\mathbf{B}_\perp| - B_{\min})\right\rangle_\Omega, \text{ and}$$

$$C_2(x_1, x_2, |\mathbf{q}_\perp|) = \left(\frac{2\mathbf{q}_\perp^i\mathbf{q}_\perp^j}{\mathbf{q}_\perp^2} - \delta^{ij}\right)\left\langle \int d^2\mathbf{B}_\perp \mathcal{M}^i(x_1, x_2, \mathbf{q}_\perp, \mathbf{B}_\perp)\mathcal{M}^{\dagger,j}(x_1, x_2, \mathbf{q}_\perp, \mathbf{B}_\perp)\Theta(|\mathbf{B}_\perp| - B_{\min})\right\rangle_\Omega$$

Isobar shapes - JIMWLK evolution

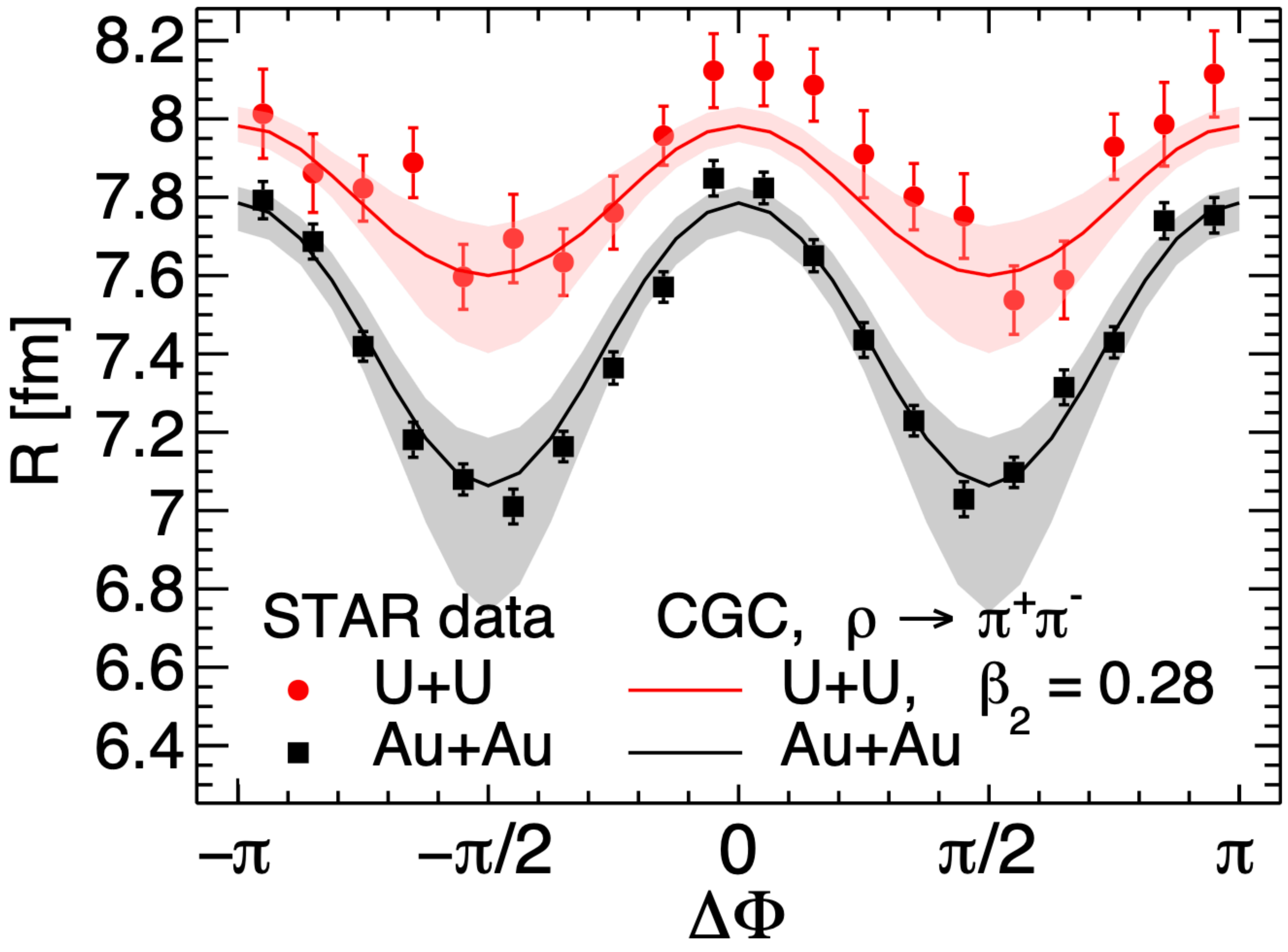
G. Giacalone, B. Schenke, S. Schlichting, P. Singh

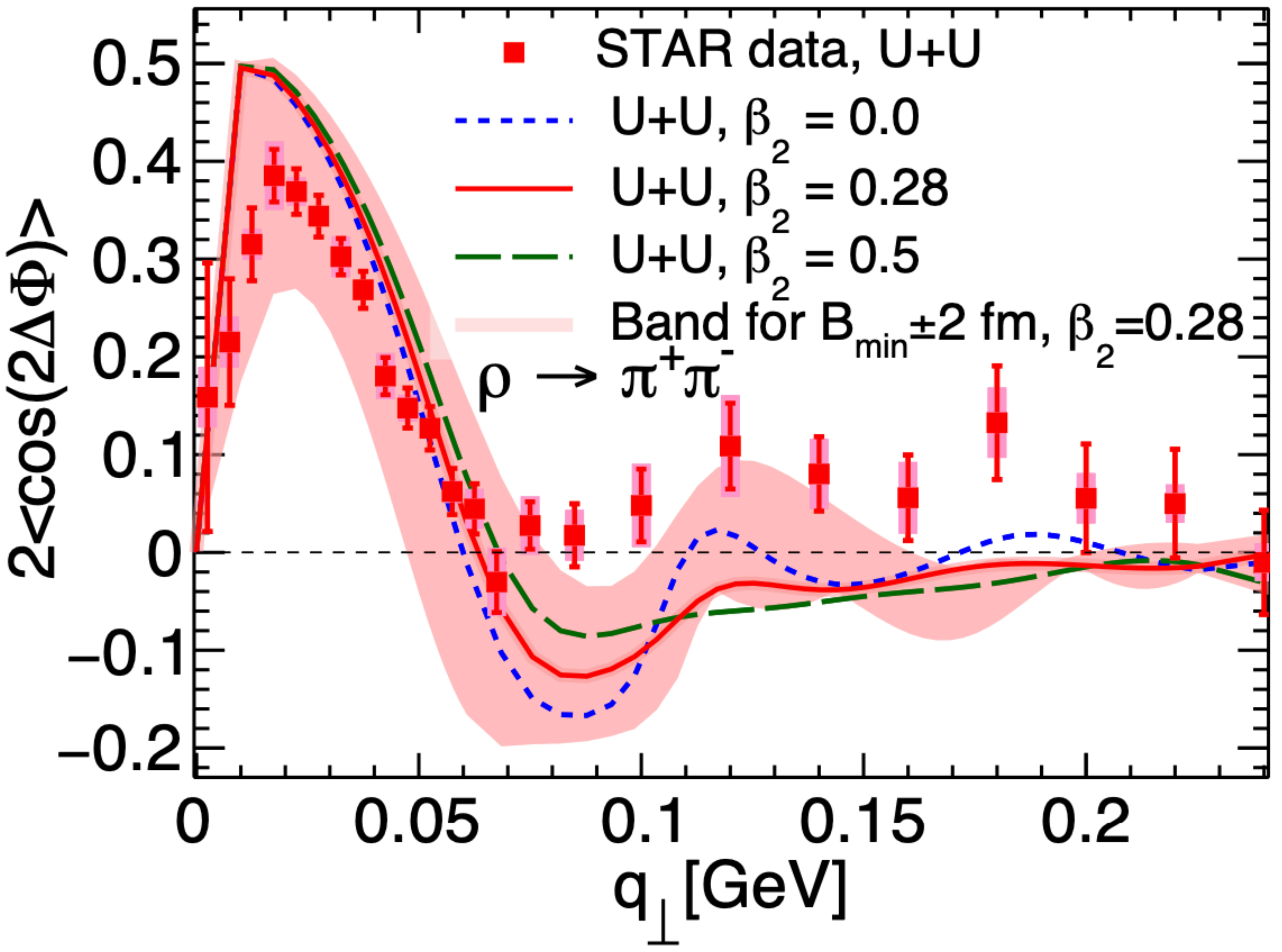




Effects of nuclear radius and deformation

Heikki Mäntysaari, Farid Salazar, Björn Schenke, Chun Shen, Wenbin Zhao, arXiv:2310.15300

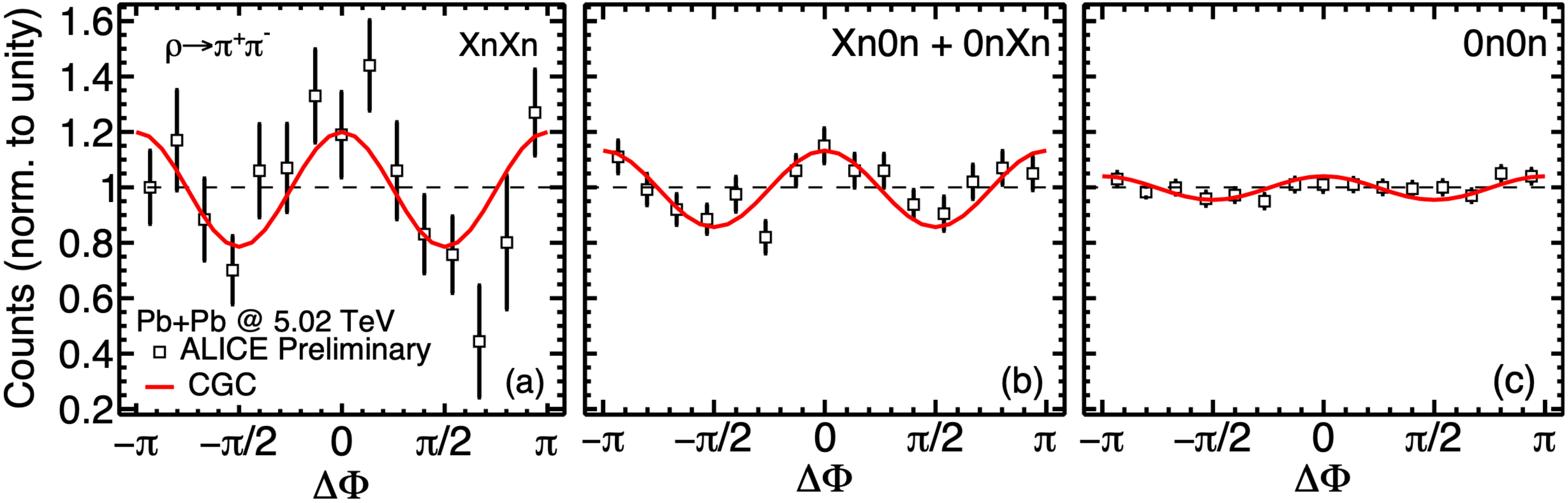




Large effect from the differences in minimal impact parameter B_{min}

Varying impact parameter distribution at LHC

Heikki Mäntysaari, Farid Salazar, Björn Schenke, Chun Shen, Wenbin Zhao, arXiv:2310.15300



More neutrons in the forward direction prefers smaller impact parameters
Modulation decreases for larger impact parameter